Crust Management for Optimal Anaerobic Digestion Performance at Meat Processing Facilities

PROJECT CODE:	2017-1033
PREPARED BY:	Bernadette McCabe, Thomas Schmidt and Peter Harris National Centre for Engineering in Agriculture, University of Southern Queensland
DATE SUBMITTED:	31 August 2017
DATE PUBLISHED:	30 November 2017
PUBLISHED BY:	AMPC

The Australian Meat Processor Corporation acknowledges the matching funds provided by the Australian Government to support the research and development detailed in this publication.

TABLE OF CONTENTS

1.0 EXECUTIVE SUMMARY

The successful design and operation of covered anaerobic lagoons (CALs) are highly sensitive to the inclusion of fats, oils and greases (FOGs) in the effluent stream entering the lagoons. While anaerobic digestion is effective for the degradation of many feedstocks, the high levels of FOGs and total solids in abattoir waste water present challenges. While the formation of crust material is advantageous in maintaining anaerobic conditions for uncovered lagoons the problem of increased crust formation and overloading over time still present problems with regard to management of the accumulated waste on site. With the increased interest in the use of CALs for the capture of biogas, the problem of crust formation is ever more pressing.

Previous work which reviewed the removal of FOGs from effluents from red meat processing plants showed there is a dearth of fundamental information on the anaerobic digestion of real Australian abattoir wastewater. This previous review work recommended that data be gathered from laboratory trials with effluent of different fat levels to determine the limiting level of FOG in the wastewater.

This project was undertaken to determine the effects of different fat levels in abattoir effluent on anaerobic digestion to address a lack of basic data on the performance of anaerobic treatment of wastewater from Australian meat processing plants. The project was conducted over a 14 month period integrating a literature review, lab scale studies and site data analysis to establish key criteria for the management of FOGs in waste streams.

A detailed waste mapping exercise was carried out on one site. High-fat waste streams for subsequent lab scale trials were selected based on the results of the mapping exercise. The lab scale studies took on two points of foci: 1. To examine the effects of different fat levels in abattoir effluent on anaerobic digestion under controlled conditions of optimum mesophilic temperatures (38°C) and stirring while maintaining optimum alkalinity and 2. To investigate the effect of temperature and agitation on crust/foaming layer development.

The combination of literature review and engagement with a total of three sites shows that there are four key industry-wide operational issues which contribute to the formation of crusts on CALs. These relate to:

1. Inadequate primary pre-treatment which fail to reduce wastewater fat levels;
2. Poor waste stream management practices leading to spills and shock loadings to the CAL;
3. Lack of process monitoring of the CAL resulting in physical and chemical parameters outside the optimum range thereby affecting the anaerobic digestion process;
4. Installation of poorly designed CAL technology which is unable to degrade high strength abattoir wastewater at desired organic loading rates and hydraulic retention times.

The results of the first lab scale investigation showed that anaerobic digestion performance was not impacted negatively when lab scale reactors were operated over a period of more than 13 months at optimal conditions of temperature, stirring and addition of magnesium hydroxide to maintain optimal alkalinity levels. The experiment showed that even high FOG concentrations of up to 10,688 mg/L did not cause crust formation in the reactors.

The outcomes of the controlled experiment prompted the next phase of work which considered the effect of ambient temperature with or without stirring on anaerobic digestion performance and the development of crust/foaming layers when compared to a similar system at optimum temperature (40°C) with stirring. This was conducted over a 70 day period using lab scale CSTR reactors to emulate field conditions of a CAL operated without stirring at 26°C which reflects the observed minimum effluent temperature within a CAL during a winter season in temperate climates.

The characteristics of the high-fat wastewater used in the second experiment ranged from 354 to 570 mg/L for volatile fatty acid (VFA) concentration and 530 to 5,385 mg/L for FOG. The formation of a crust/foam layer was only observed in the reactors which were unstirred at ambient temperature (26°C). Poor process stability, as determined by lower levels of alkalinity and pH and high accumulation of VFAs, was evident in both stirred and unstirred reactors at 26°C compared to stirred reactors set at 40°C. Biogas production started to rapidly decline from day 50 in both stirred and unstirred reactors highlighting the importance of maintaining optimum mesophilic temperatures.

This second lab scale study suggests that it is difficult to specifically determine the maximum loadings of FOG that can be managed within anaerobic digesters. The investigation has highlighted that several factors can influence anaerobic digestion performance including temperature [ambient mesophilic (26°C) versus optimum mesophilic (40°C)] and the specific composition of the wastewater, including the relative level of FOG which contributes to COD loading and the level of nitrogen which contributes to alkalinity levels.

The outcomes of the project have identified the following key criteria for the management of FOGs in waste streams to assist industry in determining ideal plant operation to achieve optimal crust management and biogas production:

1. **Effective primary treatment** of the wastewater is essential to break down FOG into a dispersed and useable form or to ensure removal of excess FOG and solids. Primary treatment includes the use of:

- Screens (include static, vibrating, rotary, and screw presses) as the first stage of primary pre-treatment to remove solid material including fat particles, paunch and manure from the wastewater;
- Well –designed saveалls which remove fat effectively;
- Adequately operated dissolved air flotation (DAF) systems.

2. **Good waste stream management practices** to avoid excessive loading rates which can lead to continuous crust formation. Shock loads can cause an accumulation of degradation products and by-products. Consequently, a digester can become overloaded, and the probability of excessive crust formation is high.

3. **Routine process monitoring of the CAL** to ensure key physical and chemical parameters are operating within the optimum range thereby ensuring efficient degradation and maximal biogas production.

4. **Installation of correctly designed CAL technology** which is able to degrade high strength abattoir wastewater at desired organic loading rates and hydraulic retention times. The CAL

technology should take into account the degree of recirculation for mixing and ability to maintain optimum mesophilic temperatures.

The results of the lab scale trials using wastewater from an existing full-scale CAL in combination with field observations of CAL performance indicates that fat must be removed from the effluent to a level of < 300 - 400 mg/L and temperature maintained above 28-30°C. Alternatively, CAL technology which incorporates heating and stirring systems with the addition of chemicals to maintain optimum levels of alkalinity are required to degrade high-fat waste streams with FOG levels greater than 500mg/L. The lab scale investigations should be complemented by continued investigations of the performance of existing and new covered anaerobic lagoons.

2.0 ABBREVIATIONS

AD	Anaerobic digestion
AMPC	Australian meat processor corporation
BOD	Biochemical oxygen demand
$CaCO_3$	Calcium carbonate
CAL	Covered anaerobic lagoon
CH_4	Methane
CO_2	Carbon dioxide
CoHRAL	Covered high-rate anaerobic lagoon
COD	Chemical oxygen demand
CSPE	Chlorosulphonated polyethylene
DAF	Dissolved air flotation
FOG	Fat, oil and grease
fPP	Flexible polypropylene
HAcEq	Acetic acid equivalence
HDPE	High-density polyethylene
HRT	Hydraulic retention time
LCFA	Long-chain fatty acids
LLDPE	low linear density polyethylene
NH_4-N	Ammonium as nitrogen
NOx	Oxides of nitrogen
ORP	Oxidation-reduction potential
PVC	Poly-vinyl chloride
R-EIA	Reinforced ethylene interpolymer alloy
RMP	Red meat processing
TA	Total alkalinity
TBP	Tributylphosphate
TN	Total Nitrogen
TSS	Total suspended solids
VFA	Volatile fatty acids
VSS	Volatile suspended solids

3.0 INTRODUCTION

3.1. Background

Findings within the red meat industry indicate that improved fat, oil and grease (FOG) removal is required to ensure stable and optimal performance of covered anaerobic lagoons (CAL). The fats removed from waste streams also represent a valuable resource in the form of saleable low grade tallow which can offset the costs of plant operation. FOG and other solids such as paunch material can be problematic in the successful commissioning and running of CAL technology due to the formation of floating crust/scum that form. Indeed, this is believed to be one of the major factors which hinder the successful uptake of CAL technology in the red meat processing (RMP) industry. With a number of full-scale CALs now installed there is an emerging need to understand the key operational elements of CALs and the impact that crust formation has on this technology.

The floating crust, scum or foam layer that forms on the surface of the lagoon is believed to be largely a combination of floating solid, fats, oils and greases, matted hair and other fibrous material. The crust can accumulate in varying thickness and have the following negative impacts on a CAL performance and cover materials. Project A.ENV.0072 performed by Golder Associates Pty Ltd in 2009 reported on the assessment of available cover materials for CALs. The report also provided a list of negative impacts of scum/crust layers.

As well as contributing to scum/crust layers, FOG has been shown to negatively impact digestion processes at high concentrations and leads to treatment upsets. There is thus a need to understand key operational processes both upstream of the CAL and the AD process within a CAL in order to:

1. Reduce FOG and total solids before they enter the lagoon in the first instance, and

2. Maintain efficient CAL operations which utilise any FOG loads which enter the lagoon to minimise crust formation whilst optimising biogas production.

Conventional CAL technology is becoming increasingly advanced, integrating heating and stirring options among other mechanisms which have the potential to enhance the availability of FOG in the biodegradation process. In recent times, several plants across the industry have been investigating the commissioning of CALs including covered high rate anaerobic lagoons (CoHRAL). Thus further work is required to better understand the design and management implications of FOG removal and the role of ancillary equipment (i.e. dissolved air flotation; DAF) and waste stream characteristics to ensure the successful adoption of CAL technology.

3.2. Summary of previous industry reports

A number of previous AMPC/MLA commissioned studies on the use of CALs to treat abattoir wastewater and capture biogas have reported the impacts of FOG on CAL operation and CAL covers (for example, Thomas Foods Murray Bridge facility in South Australia and JBS Australia’s former King Island meat processing facility). Table 1 provides a list of industry supported reports and summarises the main findings

Table 1: Summary of industry reports related to abattoir wastewater treatment using CALS and crust/scum issues

PUBLISHER, YEAR, PROJECT NUMBER	TITLE	SUMMARY
AMPC, 2015 (no project No. provided)	Review of removal of fats, oil and greases from effluents from meat processing plants	Overview on treatment of effluent from meat processing plants with high fat content in covered anaerobic lagoons, pre-treatment options, and technological aspects.
MLA, 2009, A.ENV.0072	Anaerobic cover material vulnerability	The report considered potential materials for anaerobic ponds and summarised performance of cover materials for various selection criteria.
MLA and AMPC, 2012 A.ENV.0135	Covered anaerobic lagoons	The report generated useful, industry specific data on the rationale behind alternative CAL technologies and what makes them viable. Project output included guidelines for application of CALS for RMP industry, citing issues, and design/operational practices
MLA, AMPC, MDC, 2012 P.PIP.0290 (also see RIRDC, 2013, PRJ-005673)	Demonstration of covered anaerobic pond technology	Reported on performance of a CAL on King Island through intensive monitoring for 7 months from commissioning. Solids accumulation in CAL was evident in the CAL within 6 months of operation. Some crust build up was evident under the cover despite the low FOG concentrations. Reports highlights that this remains an important issue for CAL longevity.
MLA, 2016, P.PIP.0460	Investigating potential benefits of biomass recirculation in a covered anaerobic lagoon	Results found insignificant improvement on the biogas production and organic treatment performance during both biomass recirculation modes despite success in sludge resuspension through the upper volume of the CAL.
MLA, 2012, A.ENV.0131	Energy and nutrient analysis on individual waste streams	This investigation identified 5 major sources of wastewater at the 3 meat processing facilities. It is recommended that rendering, slaughter floor, and paunch wastewater be treated using an anaerobic process (to remove carbon, and recover nitrogen and phosphorous). Cattle wash and boning room are very high flow and low contaminant, and can therefore bypass primary treatment.

Table 1 (cont.): Summary of industry reports related to abattoir wastewater treatment using CALS and crust/scum issues

PUBLISHER, YEAR, PROJECT NUMBER	TITLE	SUMMARY
MLA, 2013, A.ENV.0151	NGERS and wastewater management – mapping waste streams and quantifying the impacts	During sampling, 6 major sources of wastewater were identified at the 6 meat processing facilities included in this investigation. The composition of individual wastewater streams varied depending on the source within the slaughterhouses and ranged from low strength (boning) to very high strength (rendering) with TCOD over 70,000 mg/L, there were also large differences in the concentrations of key nutrients N, P and K. There were also indications of oil and grease inhibition when treating rendering wastewater. It is recommended that rendering, slaughter floor, and paunch wastewater should be treated using an anaerobic process.
RIRDC, 2013, PRJ-005673 (also see MLA, AMPC, MDC, 2012 P.PIP.0290)	Methane recovery and use at a meat processing facility	This report discusses the design, start-up and normal operation of a CAL, constructed at the JBS Australia's King Island meat processing facility. The project objectives where to demonstrate an efficient and effective means of producing safe and clean biogas for use as a possible renewable energy source at a processing plant through the development, fabrication, installation, operation and monitoring of a CAL.
MLA, 2013, P.PIP.0293	Design and optimisation of a purpose built covered anaerobic lagoon	This project reports on the design of a purpose built CAL for a mixed beef and sheep abattoir at Murray Bridge in South Australia. The project includes a desktop review of options and rationale for a final design recommendation for the CAL with specific analysis of key areas of risk including: the design loading rate; an effective automated sludge removal system; a long life covering structure; and a biogas collection and handling system. Importantly, this project also supports the evaluation and review of the theoretical design during the construction and commissioning phases of the CAL development. This includes analysis of any design modifications considered and/or required in translating the proposed design into a functioning plant.
AMPC, 2015	Environmental performance review: red meat processing sector 2015	This report continues a series of environmental performance reviews of the Australian RMP industry and presents results for the 2013-14 financial year.

3.3. Factors influencing the formation of scum/floating crusts

The process of crust formation in anaerobic lagoons can be attributed to a number of causes as outlined in Table 2 below. Due to the complexity of biosystems, it is difficult to relate the classification of causes to single components. Nevertheless, some correlations between crust formation and feeding of certain substrates and other incidences in the lagoon can be observed.

Table 2: Classification of the causes of foaming (adapted from Subramanian & Pagilla 2015)

CLASSIFICATION	CAUSES
Feedstock/wastewater characteristics	• Surface active agents in feed sludge • Foam causing filaments in feed sludge
Digestion process-related	• Organic loading aspects – overload and inconsistent loading • Imbalances between the successive hydrolysis, acidogenesis and methanogenesis • Gas production rate/withdrawal variations.
Digester operating conditions	• Temperature; pressure changes • Mixing intensity and patterns
Digester configuration, shape and physical features	• Digester shape and configuration • Sludge withdrawal and gas piping

From an international perspective, full scale biogas plants can be affected by serious process failures due to foaming issues. Over-acidification and the resulting change in pH, foaming and the creation of floating layers lead to operational failures or even to complete process interruptions, which result in considerable financial losses (see Figure 1). Foam formation can cause various operational disturbances and severe structural damage, spillage, damage to the gas-handling system, failures of feeders and recirculation pumps, and failures of measuring sensors, and, thus, problems in process control. The blockage of gas pipes can cause an increase in pressure within the digesters, which activates the pressure control valve, thus, leading to additional safety problems, or even damage the digester cover (Moeller *et al.* 2012). As a consequence, the usable bioreactor volume and the hydraulic retention time (HRT) reduce, the mixing state of the reactor degenerates, and the degree of degradation decreases, resulting in reduced biogas production (Moeller *et al.* 2012).

Figure 1: Floating layer in an agricultural biogas plant in Germany after failure of agitator (Feuerborn 2016)

Feedstock/wastewater characteristics

Wastewater characteristics vary significantly in the Australian RMP industry. Factors contributing to variation include species slaughtered, seasonal, weekly, daily and shift variation, infrastructure and on-site processes. While there are similarities between abattoirs, no two plants perform identically. Table 3 below compares the effluent characteristics of four different reports with residential strength wastewater. The parameters reported by Johns (1993) and White, Johns and Butler (2013) indicate FOG concentrations of only 100-200 mg/L, while much higher were measured by UNSW (1998) and McCabe et al. (2013), with the latter measuring an average ± standard deviation of 619 ± 510 mg/L. Some causes of foaming related to wastewater/feedstock characteristics will be outlined in the next section to provide some insight into the parallel problem of crust formation in Australian RMP CALs.

Table 3: Concentrations of parameters of high-strength wastewaters produced by abattoirs (Harris & McCabe 2015)

PARAMETER (mg/L)	RESIDENTIAL STRENGTH [(a)]	TYPICAL ABATTOIR RAW WASTEWATER (ALL MEATS) [(b)]	KING ISLAND (BEEF) [(c)]	SOUTHERN MEATS ex DAF (SHEEP) [(d)]	CHURCHILL ABATTOIR (BEEF) [(e)]
BOD	100-400	1,600-3,000	3,000	~1/2 COD	163-7,020
COD		4,200-8,500	7,250	3,100-11,500	1,040-12,100
FOG	50-150	100-200	120	290-2,670	5-2,110
TSS	100-400	1,300-3,400	2,000	1,150-5,700	457-6870
VSS		n/a	n/a	1,040-5,300	n/a
TN		114-148	450	180-440	296-785
NOx		n/a		0.01 – 0.12	n/a
NH_4-N		65-87	250	18-135	23.8-349[(f)]
Total P		20-30	45	26.4-60	n/a
VFA		175-400	n/a	61-600	1,020-1,980
Alkalinity		350-800	n/a	340-700	70-906

(a) Benefield (2001); (b) Johns (1993); (c) White; Johns and Butler (2013); (d) UNSW (1998);

(e) McCabe et al. (2013); (f) Value is for NH_3-N; n/a indicates not available

Fat, oil and grease (FOG)

Anaerobic digestion of FOG is complex due to the nature of lipids. Lipid-rich material enters AD systems in three forms: clumps of solid fat, globules of liquid oil, and scummy films of grease. Once these materials enter the AD system, they immediately begin to separate from the water and float to the surface due to their hydrophobic nature. Separation occurs because lipids are typically non-polar substances and are therefore immiscible in water. Lipids float to the surface as the densities of the fats are much less than that of water, resulting in the heavier material to sink to the bottom. This physical separation, and the resulting decrease in surface area to volume ratio makes enzymatic hydrolysis, the first stage and rate-limiting step of AD, difficult (Figure 2).

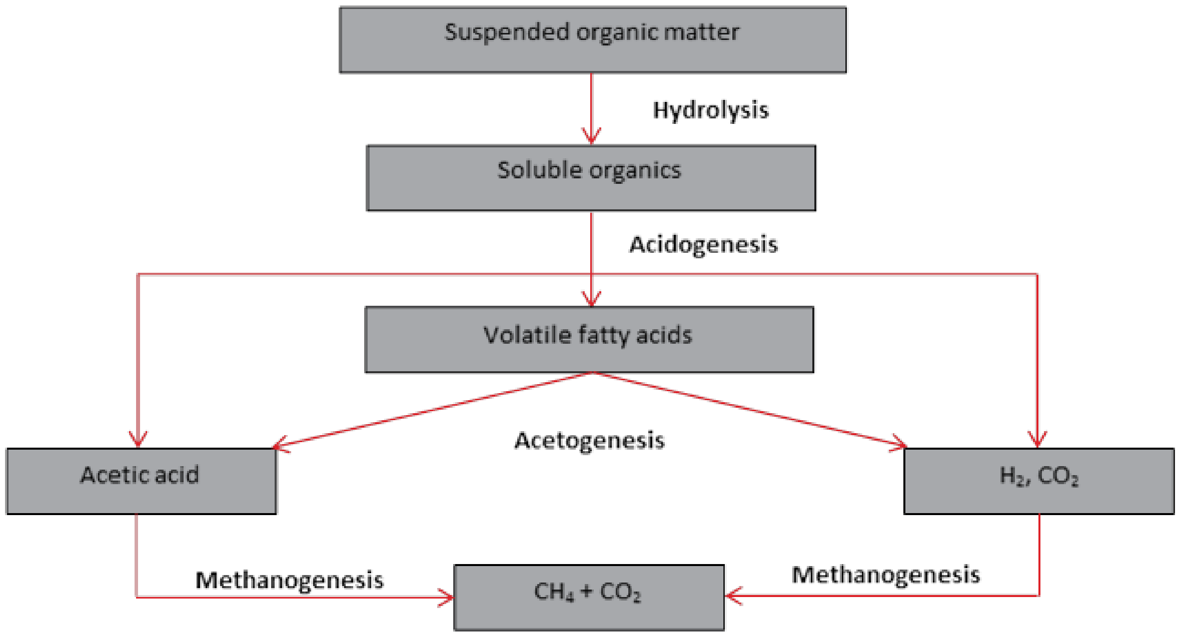

Figure 2: Stages of anaerobic digestion, modified from (Appels et al. 2008)

Hydrolytic enzymes cleave complex, suspended organic matter into their soluble counterparts. Large carbohydrates such as starches are degraded to monosaccharides, proteins are degraded to amino acids, and bound fatty acids such as triglycerides are converted to glycerol and long-chain fatty acids (LCFA). The first hurdle in the hydrolysis of FOG is access to the substrate. As mentioned, FOG floats to the surface, coalescing into a mass with a very large volume with respect to surface area. This results in very slow enzymatic degradation.

Long-chain fatty acids then adhere to the surface of the microbial cell walls and are transported to the interior of the cell for further digestion through β-oxidation. Degradation of LCFA is the slowest conversion step and controls the overall kinetics of the digestion process. The difference between the rates of degradation of triglycerides through hydrolysis and of LCFA through β-oxidation can result in an imbalance, resulting in LCFA accumulation and subsequent inhibition of microbial activity (Ma *et al.* 2015). As LCFA accumulate on the microbial cell surface, creating a physical barrier between the micro-organisms and the substrate. This barrier inhibits mass-transfer of substrates and metabolites across the microbial cell walls (Pereira *et al.* 2005). The cell membrane is also a site of further inhibitory actions. Cell membranes perform an array of functions, and are a primary target of LCFA (Ma *et al.* 2015). Surfactant properties of LCFA act to solubilise the cell membrane and membrane proteins, leading to cell lysis (Wu *et al.* 2006), enzyme inhibition (Zheng *et al.* 2005), and disruption of the electron transport chain (Desbois & Smith 2010; Ma *et al.* 2015). Furthermore, the concentration required for each particular LCFA to produce inhibition is different, and each microbe may be more or less capable of performing under a given concentration (Koster & Cramer 1987; Nieman 1954). However, given time it is possible for these microbes to acclimate to the LCFA coating, and to a degree, digest the lipids to produce biogas (Martin-Gonzalez *et al.* 2010). Secondly, due to the physico-chemical properties of FOG, once adhered to sludge, FOG tends to cause sludge to float to the surface of a lagoon or reactor (Esposito *et al.* 2012). Once on the surface, the microbes will be exposed to an oxygenated environment and will be susceptible to washing out of the system with the effluent wastewater.

Proteins

International biogas plant experiences show that proteins play a crucial role in foam formation which can lead to the development of a crust and occurs as a consequence of both feeding and microbial activity. Protein-rich waste streams include poultry manure and slaughter wastes. Proteins present in these waste streams contain high amounts of nitrogen bound in the form of amino groups. In the course of decomposition, ammonium is released. This residual ammonium can inhibit the AD process, provided it appears in the form of ammonia (Moeller *et al.* 2012). The shift in production of ammonia can be caused by several factors including temperature increase or changes in pH within the anaerobic digester. Furthermore, there is a distinct relationship between high nitrogen concentrations in the digester sludge and excessive foam formation.

Surfactants

Surface-active compounds (surfactants) are closely related to foam formation. There are two groups of surface-active compounds which relate to foam formation in biogas plants: surfactants and bio-surfactants. Surfactants include compounds such as volatile fatty acids (VFA), oil, grease, detergents, and proteins which enter the biogas reactor with the feedstock streams. Bio-surfactants are natural substances that are products of microbial activity inside the digester such as hydroxylated and cross-linked fatty acids (mycolic acids), glycolipids, lipopolysaccharides, lipoproteins-lipopeptides, phospholipids, and the complete cell surface itself. Bio-surfactants, which are responsible for both the cohesion of microbial cells forming granules and the adhesion of microbial cells on the surfaces, are also called extracellular polymeric substances (Moeller *et al.* 2012).

Digestion process-related characteristics

Crust formation can also occur as a consequence of inadequate plant management. Excessive loading rates can lead to continuous crust formation. Shock loads can cause an accumulation of degradation products and by-products. Consequently, a digester can become overloaded, and the probability of excessive crust formation is high.

The intermittent feeding of easily degradable substrates generally causes a short-term increase in biogas production. Depending on temperature and the quantity of microbial biomass, rapid carbon dioxide (CO_2) can be released immediately after feeding due to the hydrolysis of carbohydrates. If enough surfactant is available, spontaneous crust formation can start. A similar effect can result during temperature increases in the digester. Short-term temperature fluctuation can result from insufficient mixing and the subsequent development of a temperature gradient inside the digester. If the whole digester is mixed again, a temperature increase takes place in the material from the colder digester areas. Due to the lower solubility equilibrium of gases in liquids with increasing temperature, a sudden release of huge gas volumes, mainly CO_2, can occur (Lindorfer & Demmig 2016).

Digester design and operating conditions

The likelihood of excessive foaming in a biogas plant can also be connected with technological attributes such as unsuitable heating and agitating devices. An incorrectly dimensioned heating system leads to insufficient heat transfer and, in combination with inadequate agitation, finally to foam formation (Lienen *et al.* 2013). In contrast, excessive mixing causes process imbalances due to the disturbance of microbial aggregates, and can also induce crust/scum formation through the agitation of sediments. This can be brought about by ineffective sludge recirculating. Thus, the choice of the agitation system is of importance for the crust/scum accumulation in digesters.

3.4. Impact of crusts on covered anaerobic lagoons

Operation and failure

Wastewater featuring a high load of FOG is a major contributor to anaerobic digester upset in Australian abattoirs. While much of this FOG load is recovered as tallow, a significant portion of FOG passes through primary treatment options and collects in anaerobic lagoons (McCabe *et al.* 2013). As such, several problems are attributed to FOG, including pipe blockages, digester foaming, clogging of gas collection and handling systems, sludge flotation and washout, inhibition of mass-transfer of nutrients, reaction with covers, and crust formation (Cirne *et al.* 2007; Ferreira, Duarte & Figueiredo 2012; Long *et al.* 2012). Accumulation of FOG within pipes produces blockages, depending on FOG load and flow rate, within weeks or months. These blockages not only impact the digestion process, but pose a serious risk in workplaces, with incidents such as backflow and overflowing of high-strength wastewater into work areas.

While crust formation provides benefits such as odour reduction and an anaerobic environment in uncovered lagoons, a crust which has become too thick will significantly inhibit biogas release from an anaerobic lagoon system, as well as reduce the functional volume of the lagoon (Pronto & Gooch 2008). If lagoon operation is not amended to suit the changes in functional volume, the lagoon will eventually fail.

It is difficult to gauge crust accumulation and accurately determine the depth of the crust layer. Mayoh (2011) reported a crust thickness of one meter. A crust of this volume would significantly reduce the functional volume of an anaerobic lagoon, and reduce biogas capture. Furthermore, a crust of such thickness imparts great effort and difficulty to pond cleaning and maintenance (Mayoh 2011).

While some aspects of FOG loading interrupt digesters at a biological level as described in the previous sections, other issues arise at an engineering level. A major detriment of crust formation is the displacement of functional lagoon volume where treatment can take place. With sludge accumulating on the bottom of a lagoon, and fatty crust accumulating on the surface of the lagoon, a significant volume of the lagoon can be eliminated as non-functional dead space (Figure 3). As dead space increases, functional volume decreases, and subsequently, short-circuiting increases and treatment efficiency decreases (Harris & McCabe 2015).

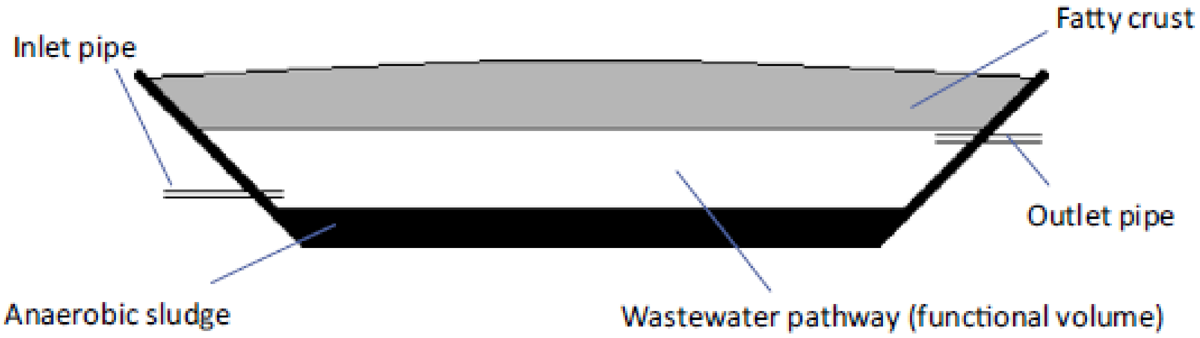

Figure 3: Illustration of dead space contributed by crust and sludge volume, resulting in a large reduction in functional pond volume, contributing to short circuiting (Harris & McCabe 2015).

Impact of crust layers on cover materials

Crust not only interacts with the hydrology and microbiology of the system, but can also impact cover materials. Scum/crust layers interact with covers in a number of ways (Golder Associates Pty Ltd (2009):

- Floating crust restricts gas pathways, limiting the permeation of gasses through the crust for collection by the cover.
- Distortion of shape, affecting gas-proofing and storm water draining.
- Expose the cover to concentrated substances.
- High cover temperatures due to solar heating can produce buoyant 'scumbergs' that place up-thrust stresses on the cover.
- FOG can plasticise and soften the polymers in the geomembrane cover material.

Furthermore, fatty crusts are difficult to remove. Meat processors at Burrangong required the services of 2 long-arm excavators and 20 people for a period of 14 days to remove a 1m thick crust, and the process was described as "challenging" (Mayoh 2011). Following removal of crust, disposal is typically burial or incineration.

There are further implications for lagoons which are covered. Crust development under a cover may produce humps in the cover, apply shear loads and localized stresses to the cover, restrict free movement of the cover during thermal cycles, and subject the cover to concentrated fatty acids, greases & oils, and their degradation products (CSIRO 2010). Contact between crust and cover material, typically high-density polyethylene (HDPE), produces a reaction which ultimately undermines the integrity of the HDPE cover.

Alternative cover materials and technology

Two industry reports have compared the properties and performance of a range of materials that can be used to manufacture pond covers (Golder Associates Pty Ltd 2009). The materials were:

- High-density polyethylene;
- Low linear density polyethylene (LLDPE);
- Flexible polypropylene (fPP);
- Reinforced ethylene interpolymer alloy (R-EIA);
- Chlorosulphonated polyethylene (CSPE).

The reports found that HDPE is the most suitable material where the cover is fixed, but it is not as flexible as other materials and may not perform well if there is rise and fall in the water level. CSPE and R-EIA are more flexible and are more suitable for variable elevation ponds, but CSPE cures with time and R-EIA can crack and degrade at the edges if the scrim reinforcement is left exposed. LLDPE and fPP are also flexible and cheaper than R-EIA and CSPE, but are not as resistant to FOG. HDPE is generally the material of choice for pond covers due to its ready availability, low cost and chemical robustness.

Generally, the design of covered anaerobic lagoons has remained unchanged in recent years. One relatively new development was made by Sauter Biogas GmbH from Germany by combining lined lagoons with a double membrane inflated air foil, which are widely used with continuous stirred tank digesters (Figure 4 A and B). This technology uses low-density polyethylene for the inner gas proof membrane and polyvinylchloride-coated polyester fabrics for the outer membrane. Additionally, an innovative mixing system is used. The liquid is sprinkled on the surface by one or more adjustable nozzles, allowing the development of different zones in the lagoon to control the digestion process and avoid the formation of floating layers. Further advantages of the system compared to traditional anaerobic lagoons are higher resistance to ultraviolet radiation and weather due to the double layer membrane, no requirements for storm water removal and external gas storage, and stable gas pressure.

Figure 4: A) Anaerobic lagoon with double membrane roof and B) sprinkling nozzle (Sauter Biogas GmbH)

Table 4 outlines strategies that are nominally put in place in overseas biogas plants to reduce foaming, but some of the strategies are not applicable to covered lagoons.

In the case of international biogas operations emergency measures can reduce the risk of technical damage caused by foaming by lowering the filling level inside the digester to widen the distance between the foam and the gas pipes or by adjustment of stirrers and reduction of substrate addition.

The most commonly applied solution to suppress foaming in biotechnological processes is the addition of antifoams. Antifoams are defined as surface active chemical substances that, when dispersed in the foaming media, will destroy the foam by causing bubble coalescence. The antifoam efficiency depends on various parameters, and a certain antifoaming agent may not be suitable for every application (Routledge and Bill, 2012). One important parameter defining the suitability of the chemicals to be used as antifoaming agents, especially for a biological process, is toxicity. Tributylphosphate (TBP) for example has excellent antifoam efficiency in various processes. However, when TBP was applied in AD systems for biogas production, fatal inhibition of methanogenesis was recorded both in batch and continuous feeding reactors (Kougias et al. 2015).

Many marketable types of antifoams, suitable for bioprocesses, are derived from fatty acids or oils. Even vegetable oils, e.g. rapeseed oil, and biodiesel can be effectively used as an anti-foaming agent for lipids containing substrates (Kougias et al. 2015). However, in contrast with commercial antifoam products, the required dosage of vegetable oils and biodiesel increases significantly with prolonged periods of application (Lindorfer & Demmig 2016).

Buffering products are another type of antifoam additive that alter the alkalinity, or buffering capacity of the system. Examples include sodium bicarbonate, sodium carbonate or urea. These types of additives affect the surface tension inside the digester thus reducing foam formation. Positive effects were mainly reported from waste water and manure-based installations. However, only slight positive results occur when treating waste which already has a high alkalinity such as those treating substrates with a high ratio of protein-rich substrates in the feedstock mix (Lindorfer & Demmig 2016). This may well be the case when using abattoir waste water.

Table 4: Measures against foaming in praxis-scale biogas plants (Lindorfer & Demmig 2016)

Strategy	Measures
Emergency measures	• Lowering of the filling level • Reduction of feeding • Adjustment of stirrers and mixing devices
Application of anti-foam additives	• Commercial anti-foam products • Vegetable oil or bio diesel • Buffering additives
Avoidance of foam supporting feedstocks	• Reduction of foam supporting substrates • Feeding these substrates into the secondary digester or effluent storage • Change of feeding intervals
Resolving process upsets	• Application of trace elements if necessary • Avoidance of inhibitors, re-inoculation after toxication • Reduction of feeding after overfeeding
Changing physical-chemical conditions	• Change of viscosity • Controlled change of temperature • Change in alkalinity
Changing mixing and feeding strategy	• Shortening pauses between mixing intervals • Shortening of pauses between feeding intervals • Variation of mixer speed and/or direction
Technical measures	• Installation of fan nozzles • Installation of an overflow pipe at filling level height • Installation of a mixer at filling level height

Some of these strategies adopted at international biogas plants may have some application at Australian abattoirs. The following sections outline some further strategies that are currently performed or should be implemented at Australian RMP sites.

3.5. Options to minimise crust formation

Waste stream management and pre-treatment requirements

Effective management of the waste streams entering an AD system is ideal for maintaining optimal biogas production. Such management is multi-faceted, requiring an understanding of AD operation, of waste stream parameters and their concentrations, and an ability to re-direct waste streams from the AD system to a more appropriate alternative. In the context of limiting crust accumulation, this becomes difficult for the RMP industry given current practices. Even after FOG is recovered as tallow, Australian abattoirs consistently produce many several tonnes of FOG as waste per day (Jensen et al. 2014). Breaking this down to waste stream characterisation, only cattle wash and kill floor effluents contain low concentrations of FOG (Jensen & Batstone 2012). These two streams represent the greatest volumetric flow, and can thereby be used to dilute the FOG loading of other streams. Using values from Jensen and Batstone (2012), the dilution of tripe wash, which carries a FOG load of 11,638 mg/L with a daily flow of 54 m^3/day, with cattle wash, which carries a FOG load of 4 mg/L with a daily flow of 882 m^3/day, would result in a combined flow of 936 m^3/day and FOG concentration of only 675 mg/L. While this is only one example, it demonstrates the potential for both dilution of one waste stream, and enhancing the organic load in another, which may be beneficial for maintaining a healthy AD operation. What is evident through the data presented in Jensen and Batstone (2012) and Jensen et al. (2014) is that there is significant room for FOG recovery and profit generation. Assuming 100% FOG recovery, and at a value of $605/tonne, the abattoirs listed in Jensen et al. (2014) could generate $50K-$1.12M through increased tallow sales.

Primary treatment options can be separated into two categories – those that prevent known issues, and those designed to improve system performance (Laginestra 2012). The former, designed to prevent known issues, are also known as primary treatment options, and are extensively outlined in the Meat and Livestock Australia eco-efficiency manual for meat processors (MLA 2002). These primary options are capable of significant reductions in organic loading, with a particular emphasis on FOG removal. However, 100% recovery of FOG is unrealistic, and other treatment options are required to improve the wastewater quality for AD.

FOG has great potential for increasing biogas production, and small amounts of FOG in the waste stream can produce large increases in biogas production. Unfortunately, due to their relatively recalcitrant nature and the inhibitory properties of their digestion intermediates (i.e. LCFA), FOG requires some form of pre-treatment prior to their digestion to optimise yields (Mendes, Pereira & de Castro 2006). Pre-treatment methods commonly used for treatment of waste activated sludge include mechanical, thermal, thermochemical, chemical, ultrasound, bio-surfactant, enzymatic, advanced oxidative methods (Appels et al. 2008; Bougrier et al. 2006; Harris et al. 2017; Saharan, Sahu & Sharma 2011) add recent publication. Utilisation of pre-treatments may aid in the degradation of FOG, but also run the risk of over-loading the system with LCFA.

Monitoring anaerobic lagoon performance

There are many parameters that are used to indicate the condition of an AD system (Table 5). The simplest of these is the measurement of hydrogen ion concentration in the form of pH. Digesters operate optimally in an environment with a pH of 6.8-7.2. While Gerardi (2003) indicates that digestion will continue at a more extreme pH range of 6.6-7.6, digester operation should be re-configured to avoid inhibition and digester failure. While simple pH measurement is indicative of digester condition, it is a crude monitoring tool, and changes in pH are slow to occur in comparison to the underlying factors that influence pH, which typically respond much faster to changes in operation. For example, the reported optimal concentration for VFA is 50-500 mg of acetic acid equivalence per liter (HAcEq/L), with an extreme range of 2,000 mg HAcEq/L, and the optimum range for alkalinity reported as 2,000-3,000 mg $CaCO_3$Eq/L, with an extreme range of 1,000-5,000 mg $CaCO_3$Eq/L. However, concentrations for these parameters can be much higher in functional digesters. Volatile fatty acids and alkalinity operate antagonistically. As acids accumulate in the digester, the calcium carbonate/hydrogen carbonate buffer absorbs hydrogen ions, generating carbonic acid, a relatively weak acid. This mitigates change in pH, helps to maintain a stable AD environment and is represented as a ratio of VFA with respect to total alkalinity (VFA:TA). In a healthy system, VFA should be present at a ratio of 0.25-0.35:1 with respect to total alkalinity.

Other parameters that are often measured and used to understand digester condition are biogas volume and biogas composition. An uncharacteristic reduction in biogas production is typical of digester inhibition and failure. While the measurement gives no further information, it is often used as a prompt for further investigation. Slightly more informative, but often the last indicator to change, is a measurement of the biogas composition. Methane (CH_4) makes up the bulk of biogas, with a typical range of 50-80%, with CO_2 the other major component of 20-50%, and some minor gasses making up the balance. Depending on digester design and operation, methane content can reach around 95% in the measured gas, but is not necessarily representative of the raw biogas. A marked decrease in methane content and corresponding increase in other gases is an indication of digester upset. The methanogenic consortium is typically more sensitive to the extremes in digestion parameters than the other microbes. Consequently, a buildup of acids and degradation to form carbon dioxide can occur with a distinct reduction in methane formation.

Table 5: Operational conditions for acceptable activity of methane-forming bacteria and methane production, modified from Gerardi (2003).

PARAMETER	OPTIMUM	RANGE
Alkalinity (mg $CaCO_3$/L)	1,500-3,000	1,000-5,000
Gas composition		
CH_4 (% volume)	65-70	60-75
CO_2 (% volume)	30-35	25-40
pH	6.8-7.2	6.6-7.6
Temperature (°C mesophilic)	30-35	20-40
Temperature (°C thermophilic)	50-56	45-60
Volatile acids (mg HAcEq/L)	50-500	500-2,000
ORP[a]	-200	-175
VFA:TA ratio[b]	0.25-0.35:1	

[a] EPA (2002); [b] Kuglarz, Mrowiec and Bohdziewicz (2008)

While there is no current measure for optimum FOG loadings with respect to enhancing gas production, there have been investigations into the inhibitory concentrations of individual fatty acids on various micro-organisms. Oleic acid (C18:1), is reported as the most toxic LCFA to the AD process, with a minimum inhibitory concentration of 50-75 mg/L (Dasa et al. 2016). Given a typical composition of tallow (Table 6), oleic acid constitutes 47% of the fat load (National Research Council 1976). Using the lower MIC of 50 mg/L, the maximum FOG load prior to the onset of inhibition would theoretically be approximately 106 mg/L. Note that this carries the assumption of 100% immediate solubility and subsequent interaction with the sludge. Lab scale anaerobic digestion reactors can handle much larger doses because the fat is difficult to degrade, and this slow rate of degradation limits the amount of fat interacting with the sludge. Modelling which factor this variation would provide a better measure for optimum FOG loadings.

Table 6: Composition of beef fat (tallow) (National Research Council 1976)

COMMON NAME	FORMULA	COMPOSITION
Myristic acid	C14:0	3%
Palmitic acid	C16:0	26%
Palmitoleic acid	C16:1	3%
Stearic acid	C18:0	14%
Oleic acid	C18:1	47%
Linoleic acid	C18:2	3%
Linolenic acid	C18:3	1%
Other	C20+	3%

Improving fat, oils and greases degradation

Although complete recovery of FOG from the waste streams would be ideal, it is inevitable that FOG should appear in anaerobic digesters at some point. Consequently, several investigations into the consumption of FOG as a co-substrate for AD have yielded encouraging results, while other investigations have attempted to improve the bio-availability of FOG through pre-treatment of the substrate. All of the aforementioned factors need to be taken into consideration if optimal performance of an AD system is to be achieved.

There are many ways to improve biogas yield. Initially this should be achieved by optimizing operational parameters including HRT, solids retention time and organic loading rate. Once a system is operating well, co-digestion may become a solution for further enhancing biogas yield, a process which involves correction of the carbon: nitrogen ratio of the wastewater through mixing substrates. Furthermore, co-digestion of FOG with a co-substrate has been shown to significantly enhance biogas yield. A process which may further enhance the process of AD is the addition of a pre-treatment stage. This additional process is typically aimed at increasing the bioavailability of the waste organics by improving the rate of hydrolysis, the rate limiting step of the AD process.

4.0 PROJECT OBJECTIVES

The aim of this project is to determine the range of operational factors which contribute to the successful commissioning and continued operation of a CAL by understanding the fate of input effluent. The specific objectives of this project are to:

1. Identify industry-wide operational issues which contribute to the formation of floating crust/scum.
2. Understand the characteristics of abattoir effluent which increase the likelihood of floating crust/scum onset.
3. Determine operational measures which can mitigate crust build-up at both pre and post anaerobic lagoon treatment.
4. Establish key recommendations for the management of FOGs in waste streams to assist industry in determining ideal plant operation to achieve optimal crust management and biogas production.

5.0 METHODOLOGY

5.1. Identification of operational issues

An expression of interest (EOI) was sent to AMPC members sites AMPC inviting their participation in the project. The EOI requested information such as

- // Detailed information of plants waste stream management and effluent mapping.
- // Information on ancillary technologies used in the pre-treatment of waste streams.
- // Information on biogas technology in use and any issues regarding crust accumulation.

5.2. Analytical methods

Table 7 provides a list of analytical methods analyzed for 1. Characterisation of waste streams and crust and 2. Characterisation of feedstock/digester effluents and the evaluation biogas production in continuous lab scale studies.

Table 7: Analytical methods used to characterise waste streams and feedstock/digester effluent and biogas production

PARAMETER	Device/Method
Total chemical oxygen demand (TCOD)	Merck COD Cell Tests, 0-1500, 0-10,000, 0-90,000 mg/L
Total solids (TS)	Drying 105°C*
Volatile solids (VS)	Burning 550°C*
Fats, oils and greases (FOGs)	Wilks Infracal ATR-SP; n-hexane extraction
Total nitrogen (TN)	Merck Nitrogen Cell Test 10-150 mg/L
Total phosphorous (TP)	Merck Phosphate Cell Test 3-100 mg/L
Ammonium nitrogen (NH_4-N)	Merck Ammonium Test 2-150 mg/L, Ammonium Cell Test 4-80 mg/L
Volatile Fatty Acids (VFA)	Merck Volatile Fatty Acid Test 50-3,000 mg/L; for reactor samples titration with H_2SO_4*
Alkalinity	Titration with H_2SO_4*
Biogas production	µflow flowmeter, Bioprocess Control, Sweden, 0-4,000 ml/h
Biogas composition	Biogas 5000, Geotechnical Instruments UK, CH_4, CO_2, O_2, H_2S

*Liebetrau *et al.* 2016. Collection of Methods for Biogas - Methods to determine parameters for analysis purposes and parameters that describe processes in the biogas sector

5.3. Waste stream analysis and crust characterisation

An intensive and rigorous sampling campaign was run for 5 weeks on site A (see section 6.1.1). The aim of the investigation was to determine the typical waste water composition, flow and load to the downstream waste water system and to specifically understand the variability of waste streams. Measurement and analysis of volumetric flowrates was achieved using calibrated strap-on TDS-100F Ultrasonic flow meters and fixed on-site electromagnetic flowmeter (Proline Promag L 400). Flow measurements were obtained from a total of 6 waste streams.

Composite sampling of the individual waste streams was performed using ISCO portable autosamplers operated in parallel over the 5 week period.

The majority of the waste streams were sampled as flow proportional or time proportional rather than grab samples to reduce the large variability that exists in waste streams. A total of 12 samples were collected over a 24 hour period and proportionally mixed in accordance to the flow data gathered during the same period. The 12 waste streams were sampled and analysed for 9 physical and chemical parameters as shown in Table 7.

Preliminary characterisation of scum/crust formed on anaerobic lagoons and CALs at Site A was also determined. Three types of samples of scum/crust were collected to represent various types of crust formation, namely samples accumulating:

- on an open air equalisation lagoon;
- under the surface of a HDPE covered anaerobic lagoon and;
- at the inlet of an aged uncovered anaerobic lagoon

The samples were collected, transported in sealed containers and immediately transported back to the lab for analysis. The samples were analysed for a total of 5 parameters according to Table 7.

For qualitative assessment, the bulk of fatty material was removed with two aliquots of hexane. Remaining solids were washed with distilled water and recovered using vacuum filtration. Recovered solids were assessed for major constituents visually under a stereomicroscope.

For quantitative analysis, total solids, fat and total nitrogen content were measured, with a mass balance applied to estimate carbohydrate content. Total solids was determined as per standard methods. For fat analysis, known masses were added to a measuring cylinder and made up to 100 mL with distilled water and transferred to a 100 mL bottle for extraction. Samples were acidified to <2 pH and extracted with 10 mL of hexane.

Total nitrogen was measured was multiplied by 6.25 to estimate protein mass.

Carbohydrate was calculated by subtracting the mass of fat and protein from the total solids content, and assuming negligible mineral content.

$M_{CARBOHYDRATE} = M_{SOLIDS} - (M_{FAT} + M_{PROTEIN})$

5.4. Continuous lab scale studies

5.4.1. Determination of optimal operating performance using lab scale studies

Continuous digestions experiments were performed to determine the factors that minimise crust formation and subsequently optimize anaerobic digestion performance and efficiency. Two stainless steel reactors (coded R1 and R2) with respective volumes of 11 and 5.8 liters (Figure 5) were operated as duplicates at mesophilic conditions (38°C) for 412 days while increasing the loads of FOG and COD. Substrate was added once a day and the reactors were stirred continuously by propeller mixers at a speed of about 100rpm.

Figure 5: Laboratory reactors used to determine optimal operating performance

This lab scale experiment was divided into two phases, whereby the first phase comprised the start-up of the process and adaptation of the microorganisms. The second phase (from day 150 on) encompassed the increase of the FOG and COD loads. Only this phase is shown in the figures in section 6.3. From day 340 on, magnesium hydroxide (Actimag, Calix, Australia) was dosed with 0.3g/L of feedstock to the reactors to increase buffer capacity and pH. In addition, trace elements $FeCl_3$, $NiCl_2 \cdot 6H_2O$, and $CoCl_2$ $6H_2O$ were supplemented to R1 at 2.9, 0.12, and 0.04 mg/g TS.

Three different waste/wastewater streams from an abattoir at site A were used as feedstock to increase FOG loadings throughout the experiment. The mixes of waste/waste streams were based on the results of the waste stream mapping exercise results (see section 6.1) and included waste from:

- the equalization pond (EQ effluent) which contained mainly the red stream and only small amounts of green stream;
- the green stream which was higher in FOG and COD concentrations;
- a mixture of green stream and DAF sludge which was mixed with the intention to increase the FOG level in the feedstock.

Table 7 shows the analytical methods used to characterise feedstock/digester effluents and the evaluation biogas production.

5.4.2. Effect of temperature and agitation on crust/foaming layer development

Semi-continuous digestion experiments were conducted in six 10L continuous stirred tank reactors (CSTR, see Figure 6).

Figure 6: Laboratory CSTR reactors used to determine the effect of temperature and agitation on crust/foaming layer development

Rectors were heated by water bath and water jacket. Overhead stirrers with adjustable speed control were used to mix the reactor content. A window at the rector front allowed to visually observe the formation of crust/foam layers inside the reactors.

Reactors were inoculated with anaerobic sludge from a covered anaerobic lagoon and green stream from site A was used as substrate in the experiment. Substrate was added once a day. The organic loading rate (OLR) ranged from 0.5 to 0.61 g of COD per litre of reactor volume and day, corresponding to hydraulic retention times (HRT) between 11 and 46 days.

Three different variations were tested as duplicates to identify the effect of temperature and agitation on crust/foaming layer development:

1. Temperature 26°C and continuous stirring at 80 rpm
2. Temperature 26°C and minimal stirring at 50 rpm; reactors were mixed shortly before and after substrate addition (about 1 hour per day) to prevent washout of active biomass from the effluent port at the bottom of the reactor
3. Temperature 40°C and continuous stirring at 80 rpm

The temperature of 26°C was chosen to represent the minimal temperature that has been observed at the large scale covered anaerobic lagoon during winter. The 40°C represent optimal conditions for mesophilic anaerobic digestion.

Table 7 shows the analytical methods used to characterise feedstock/digester effluents and the evaluation biogas production.

6.0 PROJECT OUTCOMES

6.1. Engagement of processing sites to determine operational issues

Three AMPC members (referred to as Site A, B and C in this report) responded to the EOI and have provided the following:

- // Detailed information of plants waste stream management and effluent mapping.
- // Information on ancillary technologies used in the pre-treatment of waste streams.
- // Information on biogas technology in use and any issues regarding crust accumulation.

6.1.1. Site A

Site A is a large sized, fully integrated slaughtering, fabricating, chilling, freezing and rendering facility. Figure 7 represents waste stream management and effluent mapping. This detailed process schematic was generated by NCEA staff from site visits, discussions with site staff and the integration of previous map data.

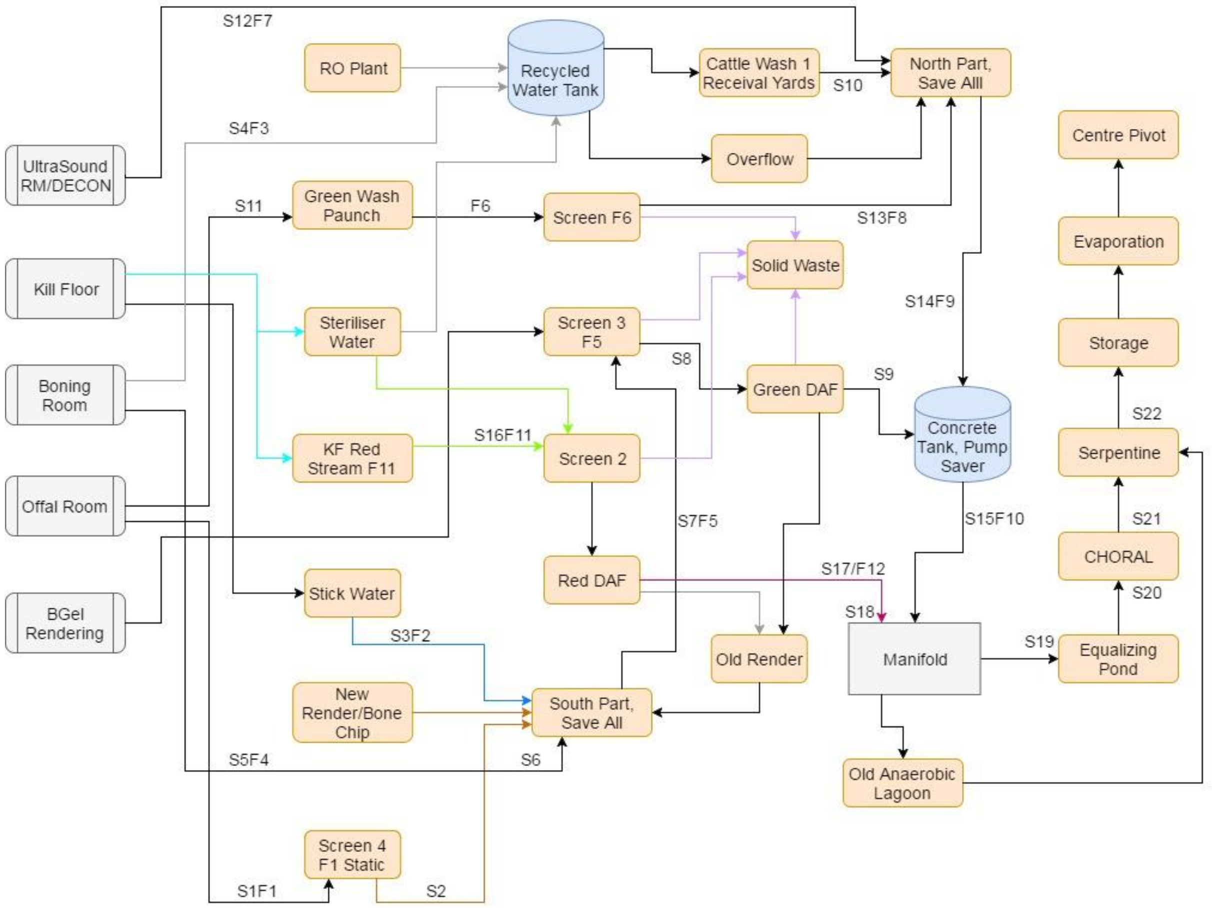

Figure 7: Detailed process schematic of waste water generation for Site A.

The waste processing operations at Site A consists of:

Slaughter Floor: All wastewater from the Slaughter/kill floor, with the exception of sterilizer water, is combined as the first major wastewater stream. This stream is sent over a rotating drum screen (contrasheer) to remove solids, and passed through a DAF to remove FOG before being sent to the anaerobic lagoon.

Paunch Handling: There are several sources of waste and wastewater associated with paunch handling, consisting of paunch, tripe/bible wash, and washdown water (designated green wash). The Tripe/bible wash comes from an automated machine wash with a cycle time of approximately 20 mins, the Tripe wash is screened to remove solids (recovered and sent with the condemned material to the rendering operation of the plant) and the liquid component is combined with stick water, render, and bone chip in the southern side of the saveall. The combined 'green' stream is subsequently sent to a rotating screen drum where the solids are removed and sent to composting, the remaining wastewater is mixed with the Cattle Wash to form the total cold effluent and sent to the anaerobic lagoon.

Paunch and green wash: Material from both streams combine in a mixing pit and are passed through a rotating screen drum to remove solid material that is then composted. Remaining wastewater combined with decontamination water and mixes with Cattle wash wastewater in the northern side of the saveall.

Tripe wash: Tripe material is passed through a screen to remove solids before wastewater mixes in the southern side of the saveall with waste from both the old and new rendering plants, stick water, and bone chip processes. Recovered solids are sent to rendering

Rendering: There are two rendering plants in operation at Oakey Abattoir, the old rendering plant handles tallow, and the new rendering plant handles bone and blood. Stick Water from both rendering plants is combined with wastewater from the boning room, the mixture is screened to remove course solids and the remaining wastewater is treated using a dissolved air flotation (DAF) unit for recovery of reusable fats (recycled to rendering). Wastewater effluent from the DAF is sent to the covered anaerobic lagoon as the total hot effluent stream.

Site A has a covered anaerobic lagoon which captures methane for on-site use. Crust accumulation was observed as due to increased organic loading rate (OLR), causing extraordinary high FOG concentrations of up to 1,430 mg/L in the wastewater, and in combination with a fast increase of the OLR and an accumulation of VFA (>600 mg/L) in the lagoon. According to the plant operator, the crust layer was visible lifting the HDPE cover. After several months of reduced feeding, degradation of the VFA, and higher temperatures during the summer, the HDPE cover had dropped to its former shape.

Crust formation was also observed on the equalisation pond during periods of reduced mixing after break down of the agitators, but didn't have any negative effect on the lagoon operation.

6.1.2. Site B

Site B is a medium sized plant that operates as an abattoir accompanied by an onsite rendering facility and farm. Figure 8 represents the waste water treatment flow chart which was provided by site staff.

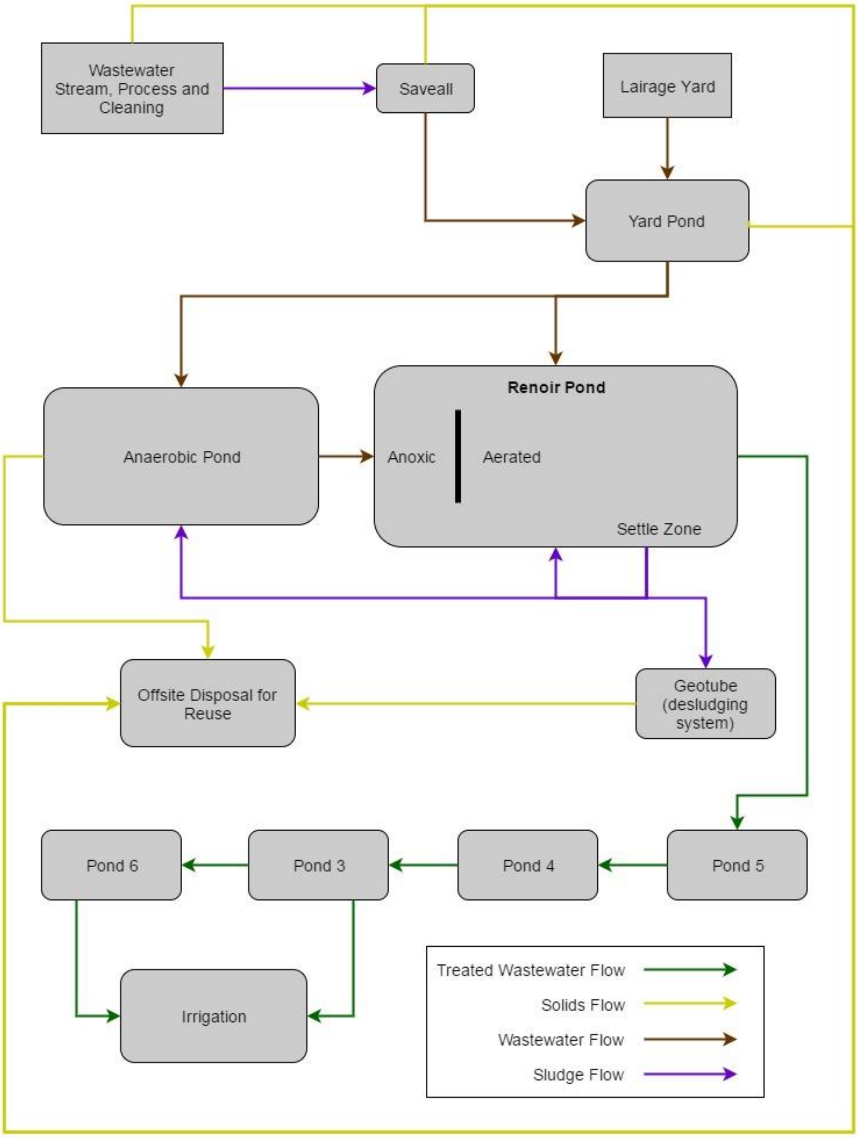

Figure 8: Waste water treatment flow chart for Site B

Waste water generated from the slaughter floor, boning room, rendering plant and cleaning processes are directed through primary and secondary treatment systems. Solid wastes and feacal material collected during processing is transferred to an offsite composting facility. Treated waste water is used to irrigate forage pastures and established crop areas.

Water directed through the contra shear to assist in mechanical screening to remove as much suspended solid matter as possible. During operations the incoming flow enters the screen drum where solids progressively collect. As the drum rotates solids are emptied from the drum into a screw conveyor. The conveyor directs the solids into tote bins where they are stored and taken off site for composting.

The combination of the contrashear and saveall assist in the removal of solids (70%) and fat (90%) from waste water. The Saveall encourages fats to float to the surface and solids to settle to along the bottom. Paddles circulate the surface and base removing fats and solids from either end of the saveall. Solids undergo dewatering prior to depositing into a large bin where the solids are then removed from site. Fats/tallows are conveyed directly into large bins where they are also removed from site.

The saveall has recently had a dissolved air flotation (DAF) system installed to improve the efficiency of solid and fat removal. A flocculant trial to maximize fat and solid removal will be undertaken once the DAF has been commissioned.

The yard pond acts as storage or settling pond for the effluent and storm water runoff from receival and lairage yards. Residency in the yard pond allows for further settling of solids. Solids are removed periodically (last done in Jan 2017) and processed off site as compost.

Majority of the waste water from the yard pond is pumped through a weir system into the anaerobic pond, with approximately 10% added as a raw feed into the RENOIR pond.

The anaerobic pond has a working volume of approximately 17ML. The effluent enters the anaerobic pond from a series of inlet pipes and will diffuse from the southern to the northern end of the pond over roughly 14 days. Recently the inlet pipes have been upgraded to deposit effluent a distance from the pond wall as to not disrupt the crust on the pond surface and lower the risk of erosion.

The RENOIR (removal or nitrogen for irrigation) pond has been designed to maximize nitrogen reduction via biological processes. The anoxic zone within the pond incorporates a raw, carbon rich feed to assist with the denitrification of nitrate. Directional aerators recycle water from aerated to anoxic zones whilst also mixing the pond contents and providing aeration. A sludge settling zone is maintained within the pond where sludge is removed via an online bleed into engineered GeoTube®.

On site there are 4 storage ponds these are labeled as ponds 3, 4, 5 and 6. These ponds vary in size from 5.0 to 12.0ML. The main purpose of these ponds is for storage allowing for excess water during times of heavy rainfall. The layout of these ponds ensures waste water has additional settling time prior to irrigation.

Irrigation water is sourced from pond 3 and pond 6 depending on the location on farm. Areas to be irrigated are maintained with grazing pastures or perennial crops assisting in the uptake and removal of nutrients.

Monitoring of the performance of the waste water treatment plant is done through routine monthly water sampling. Monthly samples assess the total nitrogen, total phosphorus, ammonia-nitrogen, nitrate-nitrogen, nitrite-nitrogen, nitrogen oxides, pH, total suspended solids and total dissolved solids.

6.1.3. Site C

Site C is a medium sized plant. Being a hot bone abattoir there are few chillers on site and subsequently is the plant does not use a large amount of water. Figure 9 represents waste stream management and effluent mapping of Site C. This map was generated by NCEA staff using a mud map provided site staff.

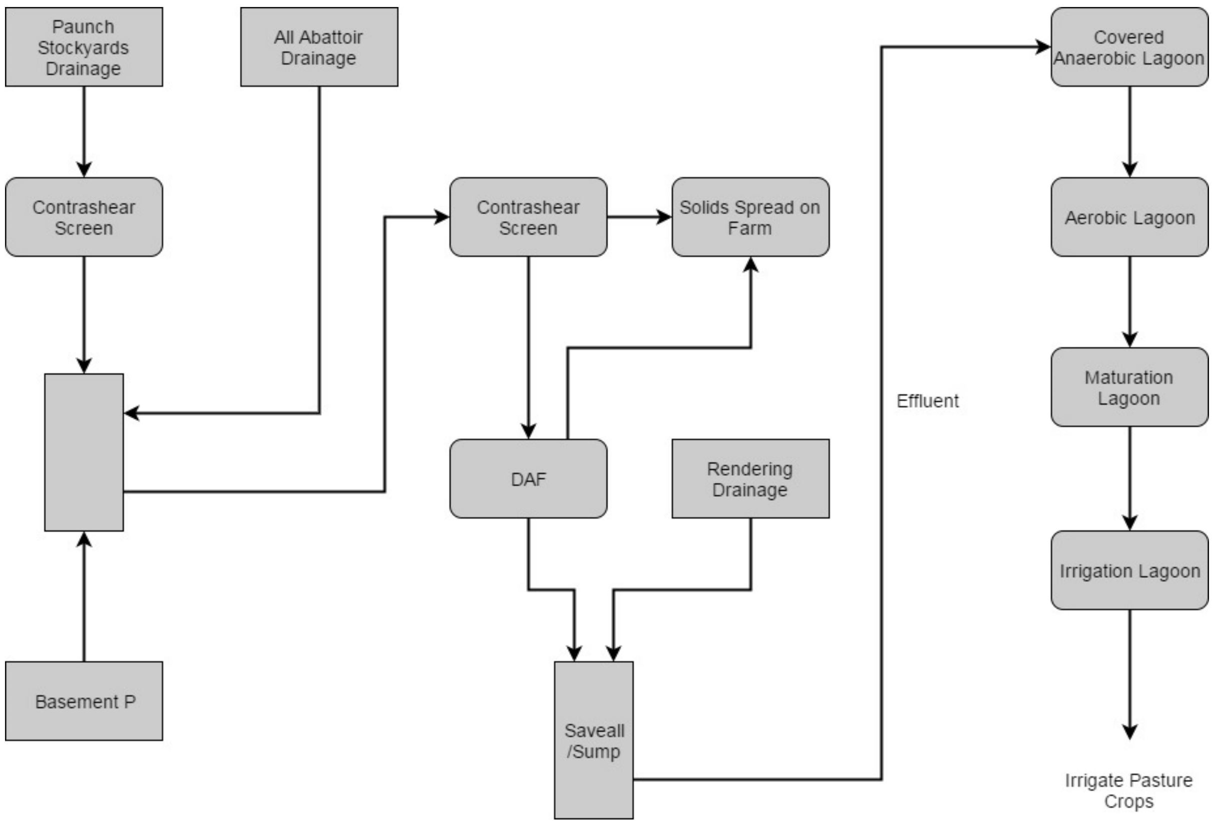

Figure 9: Effluent flow schematic at Site C.

Similarly for sites A and B, waste water is directed through primary and secondary treatment systems. Waste from both paunch and stockyard drainage and abattoir drainage is directed through two corresponding contra shear screen. Solids from the contrashear receiving paunch and stockyard drainage are sent to farmland. The saveall has a DAF installed, however, the efficiency of the DAF is poor. All waste water is then diverted to the sump.

The wastewater is treated in a covered anaerobic lagoon. The Anaerobic lagoon is 62 m x 62 m with a TWL at 57 m x 57 m, the lagoon slopes to a 20 m x 20 m bottom at a 6.35 m water depth, this gives a volume around 10ML.

After anaerobic treatment the waste water enters an aerobic polishing lagoon then a maturation lagoon. The water is held in an irrigation lagoon prior to irrigation to land.

Monitoring of the performance of the waste water treatment plant is done through routine monthly water sampling. Monthly samples assess the BOD, COD, TKN, NH4-N,, total nitrogen, total phosphorus, ammonia-nitrogen, nitrate-nitrogen, nitrite-nitrogen, nitrogen oxides, pH, total dissolved solids, total suspended solids, potassium, conductivity, oil and grease.

Although the biogas is not captured for use on site there is interest to using it in the future in the gas fired boiler. The flare does not currently operate and the cover has been recently repaired.

6.2. Waste stream analysis and crust characterisation

6.2.1. Waste stream analysis

An intensive and rigorous sampling campaign was run for 5 weeks on Site A. Table 8 (cross reference to Figure 7) provides a location description of the flows and samples obtained during the waste water sampling campaign and the corresponding sampling method applied.

Table 8: Waste water flow and sampling method

Code		Location Description	Composite sampling method
Flow	Sample		
F1	S1	Tripe wash pre-screen	Time proportional
	S2	Tripe wash post-screen	TBC
F2	S3	Stick water	Grab
F3	S4	Boning room (Total flow)	Flow proportional
F4	S5	Boning room (Partial flow)	N/A
F5	S6	Saveall South Combined sample	Flow proportional
F5	S7	Saveall South Combined sample	Not determined
	S8	Saveall South effluent post-screen	Flow proportional
	S9	Saveall South effluent post-DAF	Flow proportional
	S10	Combined cattle wash	Time proportional
	S11	Paunch/green wash combined	Time proportional
F6		Paunch green stream	Not determined
F7	S12	Decontamination	Flow proportional
F8	S13	Paunch/green wash/decontamination combined	TBC
F9	S14	Saveall North Combined sample	Flow proportional
F10	S15	Combined Saveall North and South	Flow proportional
F11	S16	Kill floor red stream	Grab
	S17	Kill floor post-DAF	Grab
F12	S18	Final mixed effluent	Not determined

Of the 12 waste streams sampled, the composition of 7 waste streams based on flow proportional data was obtained. This represents the best method in terms of reducing variability. A total of 3 waste streams were assessed based on time proportional sampling due to lack of flow data and only 3 samples were grab samples due to the inability to capture samples using the autosamplers. Figure 10 illustrates the variability of samples captured by the autosampler. Each sample represents a 2 hour interval over 24 hours.

Figure 10: Autosampler collection at combined saveall waste flow (S15) showing clear variability amongst samples over a 24 hour period.

The table in appendix 10.1 represents stream composition for all waste streams analysed. The streams can be grouped into the following categories based on contaminant strength:

1. Very strong waste streams (very high COD between >40,000 mg/L; high FOG (>6,000mg/L). These include:
   - Saveall south combined sample (S6)
   - Tripe wash pre-screen (S1)
2. Strong waste streams (high COD between >30,000 mg/L; high FOG (>5,000mg/L). This includes:
   - Saveall south effluent post screen (S8)
3. Medium - strong waste streams (high COD between >20,000 mg/L; high FOG (>1,000mg/L). These include:
   - Stick water (S3)
   - Saveall south effluent post DAF (S9)
   - Kill floor (S16)
4. Medium waste streams (COD between 5,000-10,000 mg/L; FOG up to 1,000mg/L). These include:
   - Paunch/green wash combined (S11)
   - Combined saveall north and south (S15)

- // Kill floor post-DAF (S17)

5. Weak waste streams (COD between 1,000-5,000 mg/L; FOG up to 1,000mg/L). These include:
   - // Decontamination (S11)
   - // Saveall north combined (S14)
   - // Combined cattle wash (S10)
6. Very weak waste streams (COD 500 mg/L; FOG < 50mg/L). This includes:
   - // Boning room (S4)

6.2.2. Crust characterisation

Aged uncovered anaerobic lagoon

Crust from an uncovered lagoon of operating for approximately 20 years visually contained a large proportion of fat (Figure 11 A). Figure 11 (B) shows a portion which was extracted in an attempt to improve visual clarity of the solids (Figure 11 C). Examination under a stereomicroscope shows clearly an abundance of hair, fibrous material including feed material, seeds and stalks, and fatty material (Figure 12 A). Figure 12 B attempts to illustrate the complex of hair, fibrous solids and fat that form a lattice, capturing and tying material together.

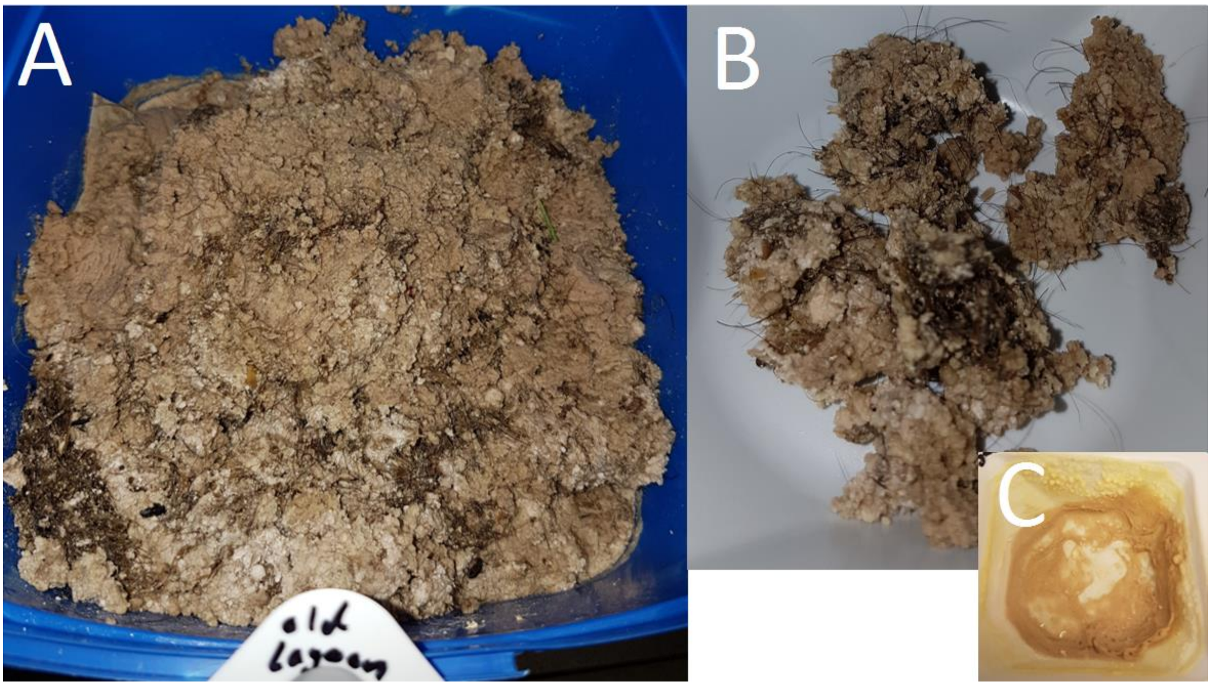

Figure 11: A) Crust sample collected from the inlet of the old lagoon. Clumps of hair are visible amongst the fatty material. B) Subsample used for qualitative assessment. C) Fatty material extracted from the subsample shown in Figure 11B.

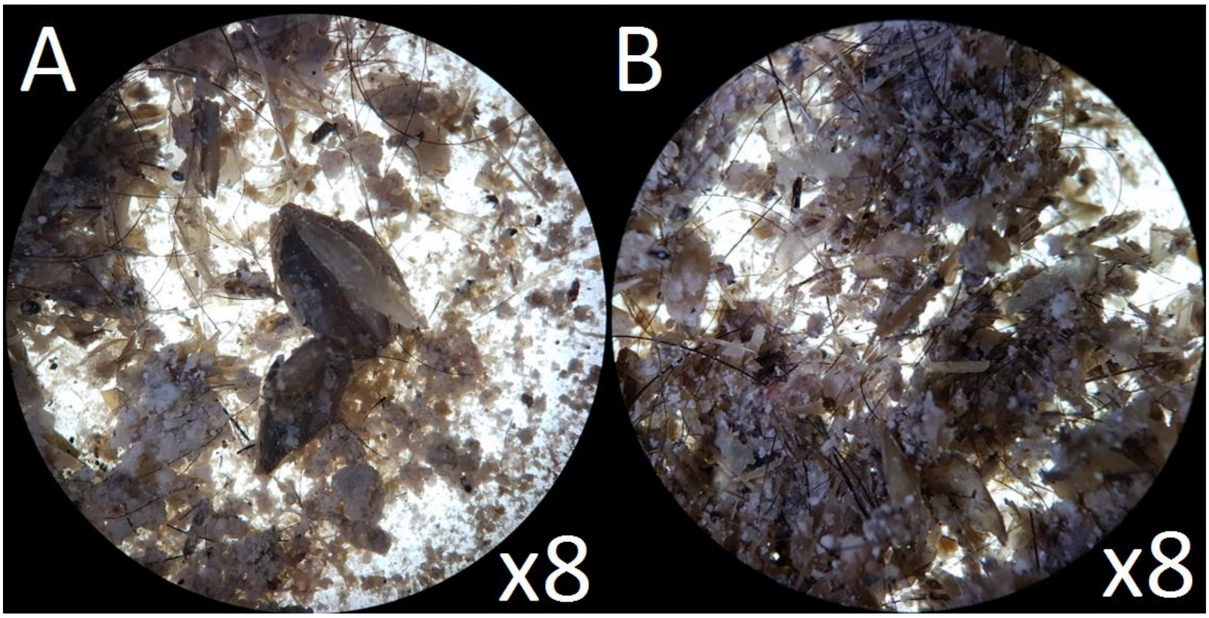

Figure 12: 8x magnification of old lagoon crust. A) Hair, fibrous material and fat are the major components of the aged lagoon crust. B) Hair, fibrous material and fat mesh together to form a mat.

Open air equalisation lagoon

Crust from the open air equalisation lagoon primarily consist of fatty material, hair and fibrous material (

Figure *13* A). Although the sample collected was much drier than that of the aged uncovered lagoon, a large proportion of fat was also recovered from this sample (

Figure *13* C). Visual assessment at 8x magnification clearly identifies semi-digested grass and grain and hair trapped in the fatty matrix (Figure 14).

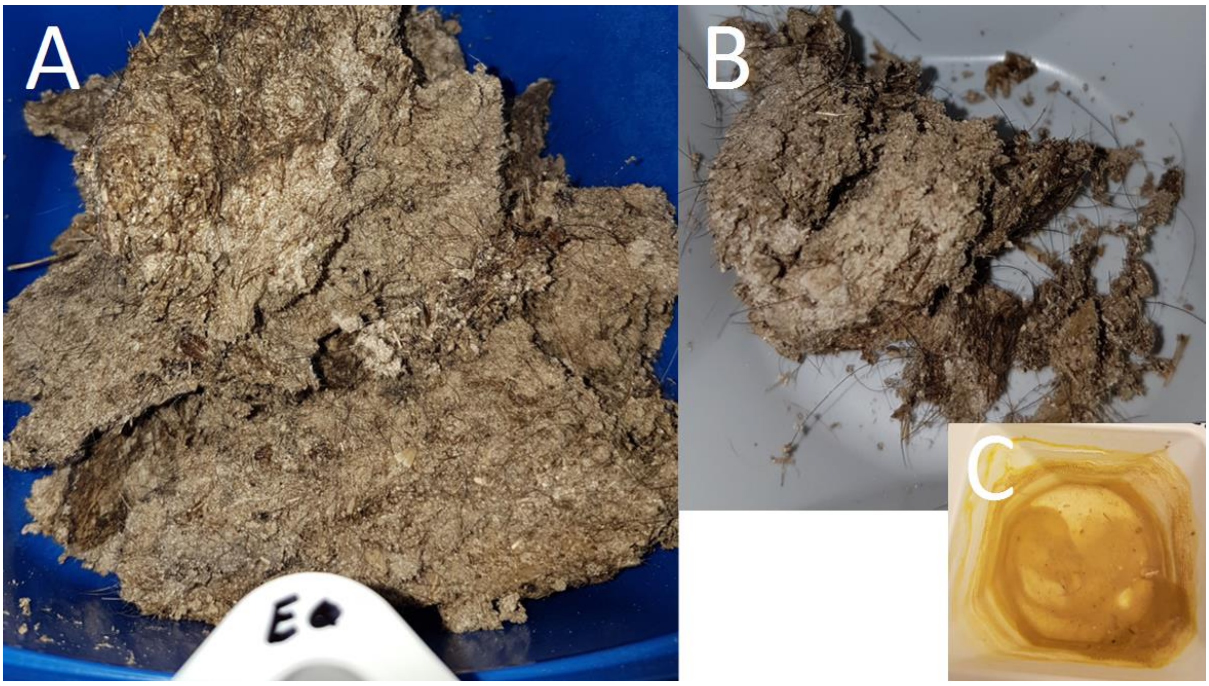

Figure 13: A) Crust sample collected from the open air equalisation lagoon. Material is dry and matted together. B) Subsample of crust sample for qualitative assessment. C) Fat extracted from the original subsample.

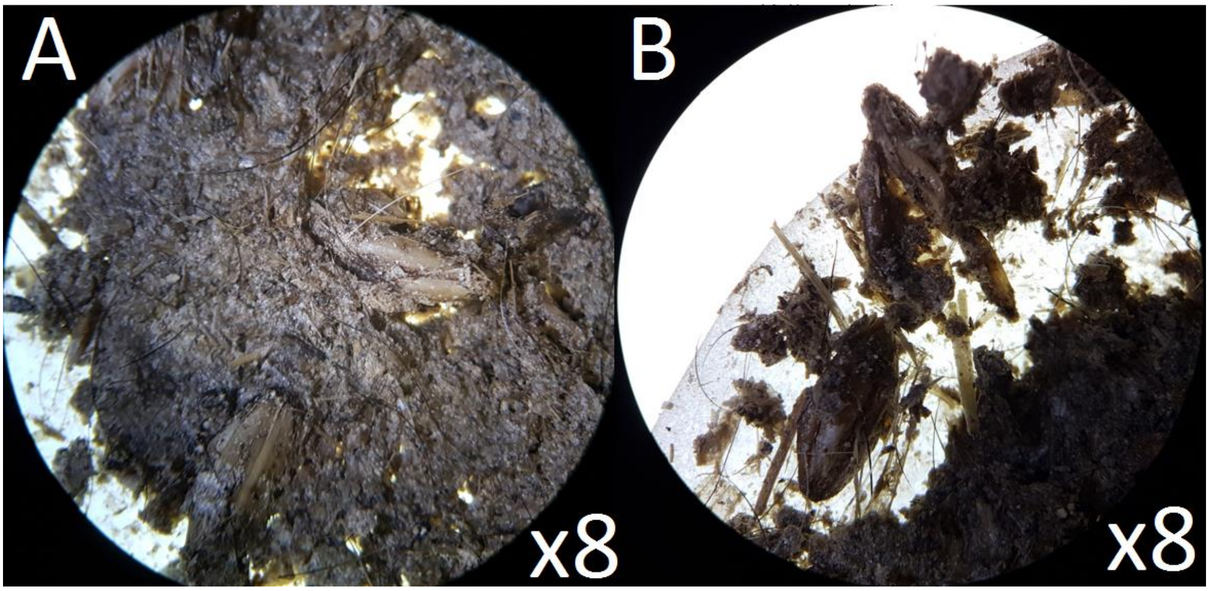

Figure 14: A) Matted hair and fibrous material in a fatty matrix. B) Grass and grain make up a large proportion of crust material.

HDPE covered anaerobic lagoon

The material collected from under the surface of the HDPE covered anaerobic lagoon (Figure 15 A) was largely indecipherable without microscopy. Visual assessment under a stereomicroscope confirmed that the majority of material was floated anaerobic sludge (Figure 16A). This suggests that the recirculation incorporated in the covered lagoon can lead to the accumulation of sludge as a floating layer underneath the cover. Hair and vegetation were present in a minor capacity (Figure 16 C). Other material present in the sludge resembled synthetic thread (Figure 16 B).

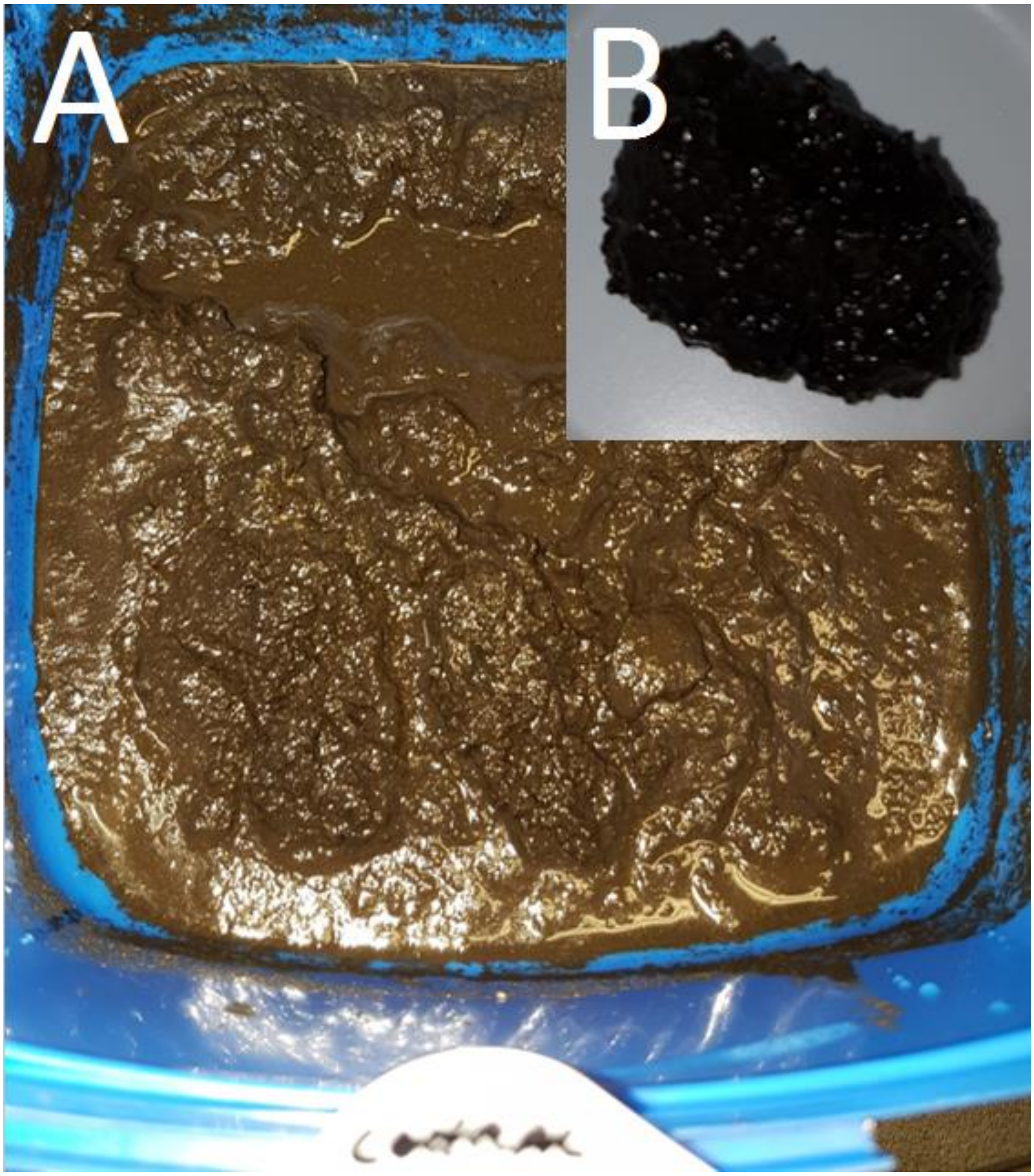

Figure 15: A) Sample collected from the sampling port on the HDPE covered. B) Subsample used for visual assessment.

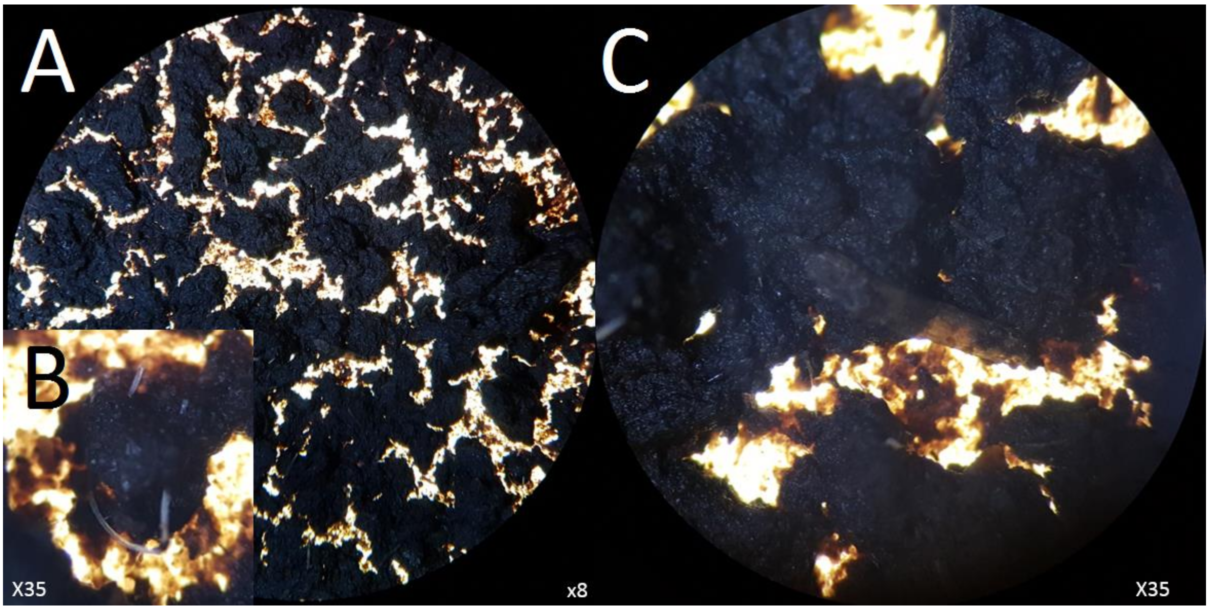

Figure 16: A) 8x magnification of HDPE covered lagoon crust material. B) Unidentified material with synethic appearance. C) Fibrous material was also present in the crust sample to a lesser degree compared to the uncovered lagoon and equalisation lagoon.

Quantitative analysis

Analysis of fat, protein and carbohydrate content revealed great difference between the samples. (Table 9). The crust on the HDPE covered lagoon was largely protein and carbohydrate, with very little fat accumulation, indicating that this material consisted primarily of floated sludge, with some lignocellulosic (paunch) material, confirming visual assessment. Similarly, visual assessment of the crust from an aged uncovered lagoon was confirmed which primarily consisted of fat and fibrous material, while equalising pond crust had a moderate fat, and high carbohydrate content. Both equalising pond and aged lagoon crust samples contained a small amount of protein, likely derived from the keratin in the hair contained in the samples.

Table 9: Quantitative analysis of crust samples for relative fat, protein and carbohydrate content.

Sample	Sample size	% FOG ± Std. Dev.			% protein ± Std. Dev.			% carbohydrate ± Std. Dev.		
Aged uncovered lagoon	2	67.08%	±	2.92%	3.98%	±	0.58%	28.94%	±	2.33%
Open air equalisation lagoon	2	30.71%	±	0.12%	6.28%	±	1.00%	63.02%	±	1.13%
HDPE covered lagoon	2	0.93%	±	0.06%	35.67%	±	1.12%	63.40%	±	1.18%

6.3. Determination of optimal operating performance using lab scale studies

Continuous digestions experiments were performed to determine the factors that minimise crust formation and subsequently optimize anaerobic digestion performance and efficiency. Two stainless steel reactors were operated as duplicates at mesophilic conditions (38°C) for 412 days while increasing the loads of FOG and COD.

6.3.1. Characteristics of the feedstock

Three different waste/wastewater streams from an abattoir were used as feedstock based on the previous sections results of the waste stream mapping exercise from Site A as described in section 5.4.1. Table 10 shows characteristics of the feedstock used in the experiment.

Table 10: Feedstock characterization

Date	Sample description	TS (% FM)	VS (% TS)	COD_t (mg /L)	pH	NH_4 (mg/L)	VFA (mg/L)	FOG (mg/L)	FOG/COD ratio
7.6.2016	EQ effluent	0.27	72.37	4,620	6.8	60	n.a.	250	5%
16.6.2016	EQ effluent	0.25	71.49	3,225	6.81	n.a.	n.a.	270	8%
14.7.2016	EQ effluent	0.23	65.89	3,595	6.83	103	543	n.a.	n.a.
3.8.2016	EQ effluent	0.24	70.97	3,565	n.a.	n.a.	n.a.	580	16%
11.8.2016	EQ effluent	0.25	71.19	3,680	6.61	126	537	860	23%
1.9.2016	EQ effluent	0.25	67.19	4,560	6.62	107	494	770	17%
22.9.2016	EQ effluent	0.25	75.92	3,600	7.18	104	472	310	9%
13.10.2016	EQ effluent	0.27	68.05	4,000	7.04	n.a.	539	370	9%
3.11.2016	EQ effluent	0.24	64.96	3,695	6.92	116	610	240	6%
24.11.2016	EQ effluent	0.46	79.60	6,375	6.27	116	767	3,300	52%
	average	**0.27**	**70.76**	**4,092**	**6.79**	**104**	**566**	**772**	**16%**
19.12.2016	Green stream	0.78	82.46	14,347	7.2	100	553	1,300	9%
18.1.2017	Green stream	0.44	75.54	6,120	7.39	n.a.	369	630	10%
1.2.2017	Green stream	0.43	72.61	5,440	7.25	n.a.	448	380	7%
6.2.2017	Green stream	0.69	75.75	12,900	6.7	152	726	880	7%
6.3.2017	Green stream	0.85	82.57	20,990	n.a.	144	1013	1,960	9%
	average	**0.64**	**77.79**	**11,960**	**7.14**	**132**	**622**	**1,030**	**8%**
18.4.2017	Green stream mix	0.70	83.75	13,500	6.55	n.a.	611	3,900	29%
18.5.2017	Green stream mix	0.71	81.80	12,290	6.42	n.a.	n.a.	3,600	29%
24.5.2017	Green stream mix	0.74	83.25	13,860	6.38	n.a.	608	3,900	28%
7.6.2017	Green stream mix	2.15	92.48	46,570	5.82	n.a.	1,028	10,688	28%
	average	**1.07**	**85.32**	**21,555**	**6.29**		**749**	**5,522**	**29%**

Figure 17 shows the daily COD and FOG addition to the reactors and the corresponding hydraulic retention time (HRT). The COD organic loading rate was increased from 0.2 to 1.4 g per liter of reactor volume and day and the FOG load from 0.02 to 0.32 g $L^{-1}d^{-1}$.

The relatively high FOG load between day 163 and 184 was caused by a failure of the DAF system at the plant, which resulted in a FOG concentration of 3,300 mg/L in the EQ effluent from 24.11.2016.

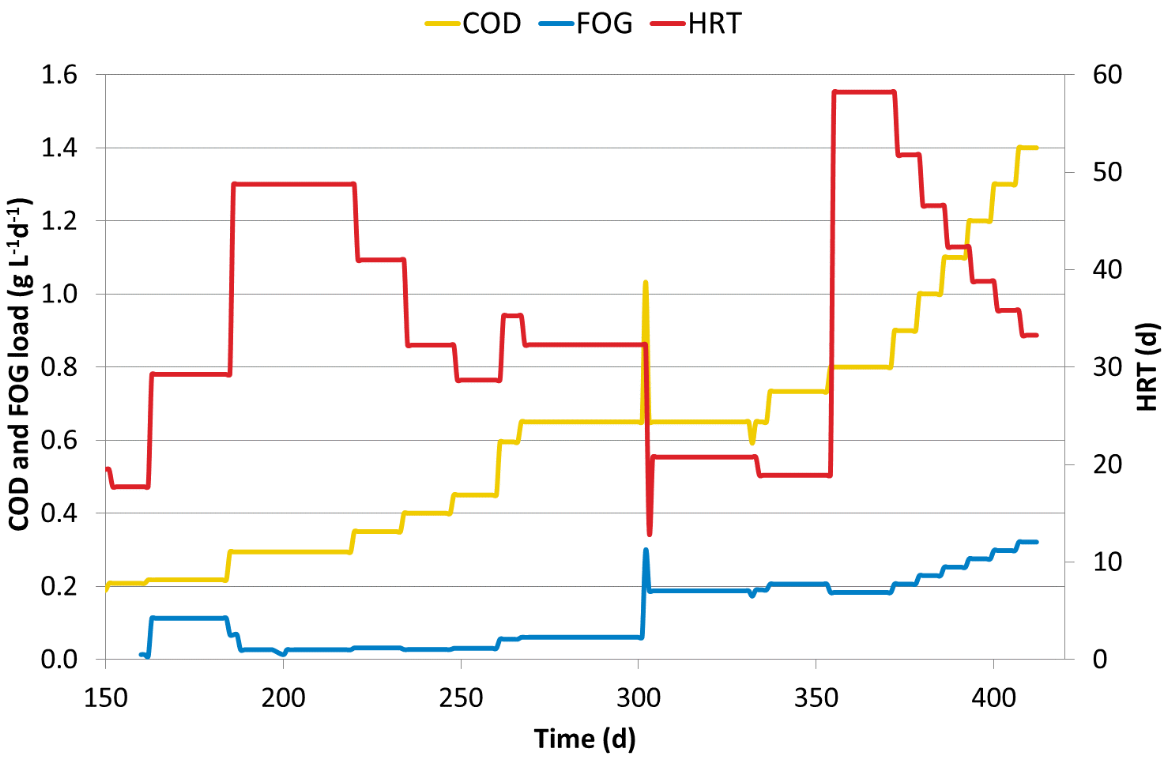

Figure 17: COD and FOG load; HRT in the reactors

6.3.2. Formation of crust/foaming layer development

Foaming and the formation of a scum layer on top of the reactor content was evaluated visually by looking into the reactors, but no significant event of foaming nor forming of a scum was observed during the whole experiment. Figure 18 shows the inside of one of the reactors after being operated with an OLR of 0.73 g COD $L^{-1}d^{-1}$ and a FOG concentration of 3,900 mg L^{-1} for two weeks.

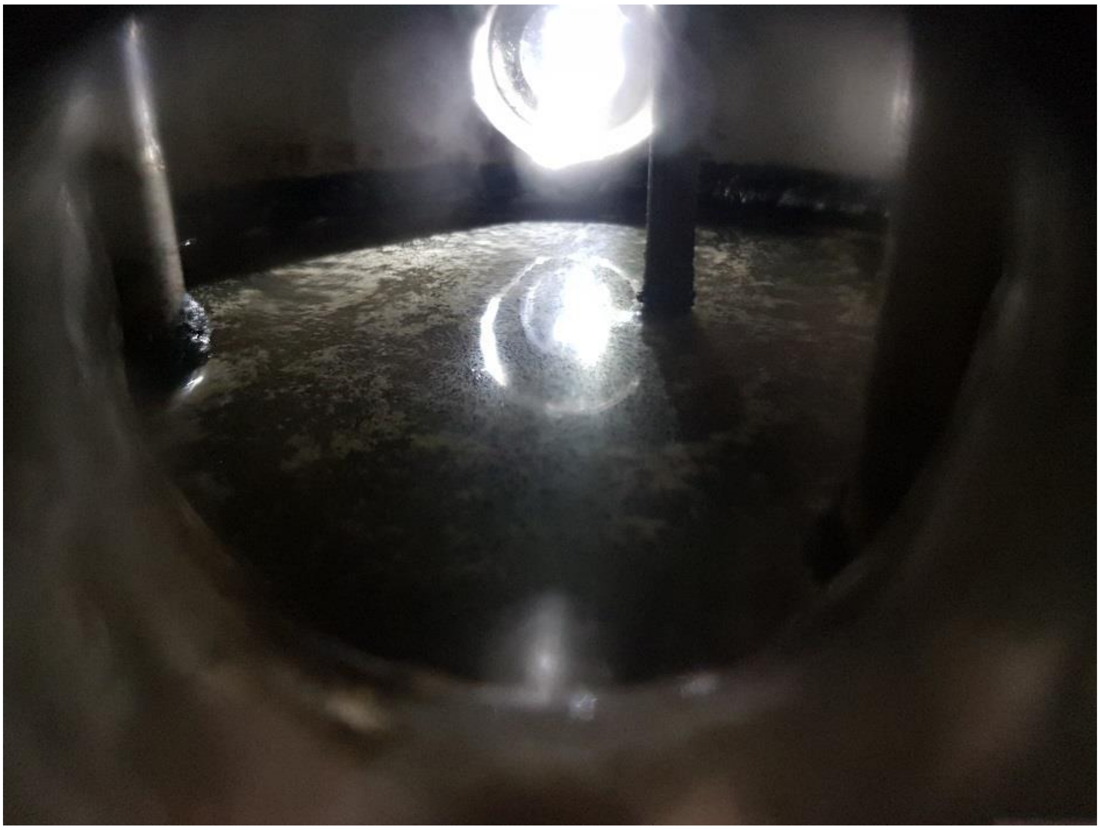

Figure 18: View of surface layer in lab scale reactor showing no evidence of scum/foaming

6.3.3. Process stability and efficiency

The parameters pH, VFA, NH4, and alkalinity were determined in samples from the reactor effluents to assess the stability of the anaerobic process (see

Figure *19*). pH values ranged from 6.7 to 7.15 and were significantly influenced by the changes in the feedstock. The addition of green stream as feedstock (day 200-300) increased the concentration of NH4-N, which acts as a buffer in the anaerobic process. Thus the alkalinity and pH increased during this period. The concentrations of volatile fatty acids (VFA) remained relatively stable with values below 350 mg/L, with a temporary peak of 444mg/L in R1. From day 340 magnesium hydroxide was dosed to the reactors to increase buffer capacity and pH.

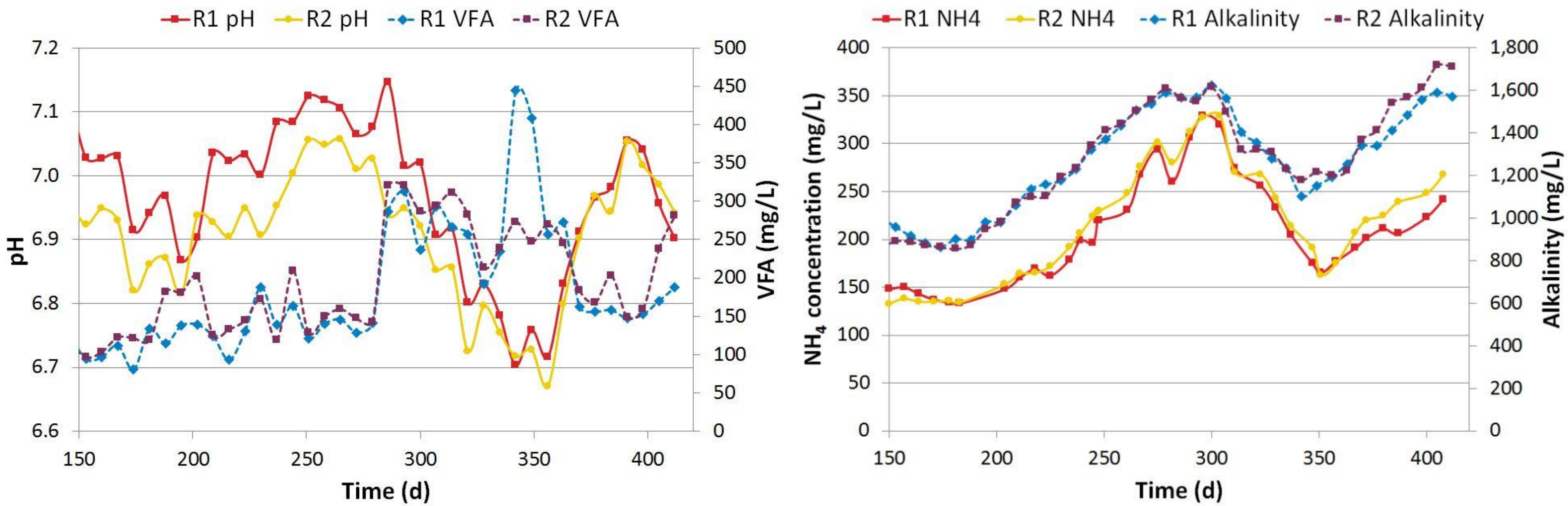

Figure 19: pH, VFA, NH_4 and alkalinity concentrations in the reactors

The degradation efficiency for COD and FOG is shown in Figure 20. COD degradation ranged from 70-95% to and FOG degradation from 80% to more than 95%.

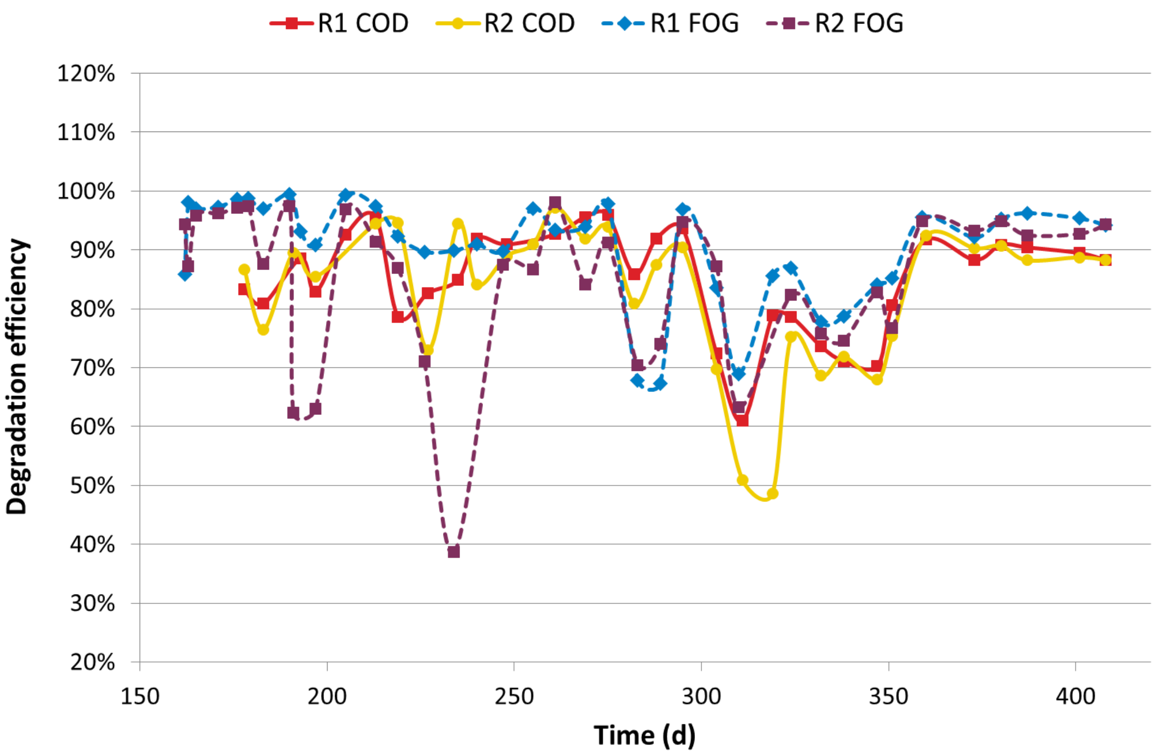

Figure 20: COD and FOG degradation efficiency in the reactors

6.3.4. Biogas quantity and quality

The production of biogas depends significantly on the feedstock concentration and composition. During the experiment between 1.5 and 26 liters of biogas were produced per liter of wastewater/feedstock and between 254 to 670 ml/g COD added (Figure 21). A key observation is the peak around day 178, which resulted from the addition of feedstock with a very high proportion (52%) of FOG regarding the total COD. The methane content of the biogas ranged from 57% to 82% with an average value of 74% (see

Figure *21*). The average values of 389 ml/g COD added, 899 ml/gVS and 74% methane content are within the range of values reported in other studies.

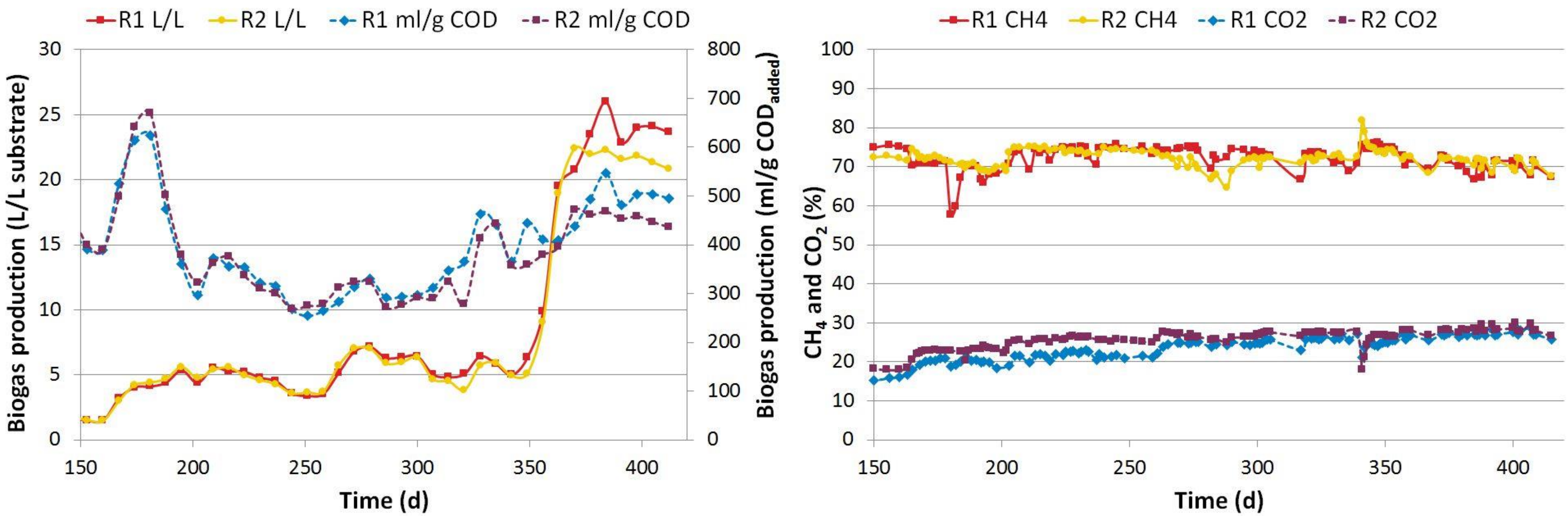

Figure 21: Biogas production per litre of feed stock and per g of COD added and concentrations of CH_4 and CO_2 in the biogas

Table 11 shows the average values for different parameters determined in the experiment. The experiment has shown, that even high FOG concentrations of up to 10,688 mg/L did not cause foaming or crust formation in the reactors. An inhibition of the anaerobic process by long-chain fatty acids was not observed. The process was stable regarding to VFA accumulation and pH value to an OLR of 1.4 g COD $L^{-1}d^{-1}$ when feedstock was added once a day. Most probably, a continuous addition would allow significantly higher OLRs. The average alkalinity of 1,282 mg/L $CaCO_{3\ Eq.}$ was relatively low compared to the recommended values (2,000-3,000 mg/L), and a higher alkalinity would be advantageous to buffer changes in pH and to prevent it to fall below the minimum threshold (≈6.5).

Table 11: Average values for different parameters determined in the experiment

	Biogas			CH_4	pH	Volatile Organic Acids	Alkalinity	FOG Degradation.	COD Degradation.
	ml/g COD_{add}	ml/g VS_{add}	L/L_{fed}	%		mg/L	$CaCO_{3\ eq.}$ mg/L	%	%
R1	395	914	8.8	74.6	7.0	185	1277	91	85
R2	383	884	8.4	73.4	6.9	196	1287	85	83

Higher alkalinity was reached in the period when 100% green stream was used as feed stock, due to the higher nitrogen level in this wastewater stream. This shows the importance of knowing the composition of the different waste streams (see section 6.2.1) to optimize the anaerobic process.

It can be concluded, that formation of foam and scum is not an issue under controlled optimal conditions; that is, using a CSTR reactor design operating at 38°C temperature with continuous stirring.

6.4. Effect of temperature and agitation on crust/foaming layer development

The outcomes of the previous lab scale investigation demonstrated that anaerobic digestion performance is not impacted negatively when lab scale reactors are operated at optimal conditions of temperature, stirring and addition of magnesium hydroxide to maintain optimal alkalinity levels.

This informed the next phase of work which considered the effect of ambient temperature and no stirring on anaerobic digestion performance and the development of crust/foaming layers when compared to a similar system at optimum temperature (40°C) with stirring. This was conducted using lab scale CSTR reactors to emulate field conditions of a CAL operated without stirring at 26°C to reflect the observed minimum effluent temperature within a CAL.

6.4.1. Sludge inoculum and feedstock characteristics

Table 12 provides an overview on the inoculum and feedstock characteristics, the organic loading rate (OLR) used, and the resulting hydraulic retention time (HRT). Green stream was chosen as a feedstock due to the higher COD, TS, and FOG levels compared to the red stream or a mixed waste-stream, to represent a stream which would result in a higher probability for crust formation. The concentrations of volatile fatty acids (VFA) and fat, oil, and grease (FOG) ranged from 354 to 570 mg/L and from 530 to 5,385 mg/L, respectively. The large differences between some of the feedstock batches result from operational changes on site and time of sampling, and had a significant effect on the HRT in the reactors, which ranged from 11.2 to 46.2 days.

Table 12: Inoculum and feedstock characteristics

	Day	TS (% FM)	VS (% TS)	COD (mg/L)	OLR (g/L/d)	HRT (days)
Inoculum		2.8	78.46			
Green stream	0-6	0.42	74.30	7,120	0.5	14.3
	7-17	1.26	87.97	23,100	0.5	46.2
	18-28	0.44	71.72	5,718	0.5	11.4
	29-37	0.89	86.34	16,360	0.6	27.3
	38-47	0.73	83.41	16,640	0.6	27.3
	48-58	0.79	83.98	17,230	0.6	28.2
	59-70	0.46	83.27	7,550	0.6	12.4

6.4.2. Formation of crust/foaming layer development

The formation of a crust/foam layer was only observed in the reactors with minimal stirring at ambient temperature (26°C). Figure 22 (A-D) shows the changes of this layer during the experiment.

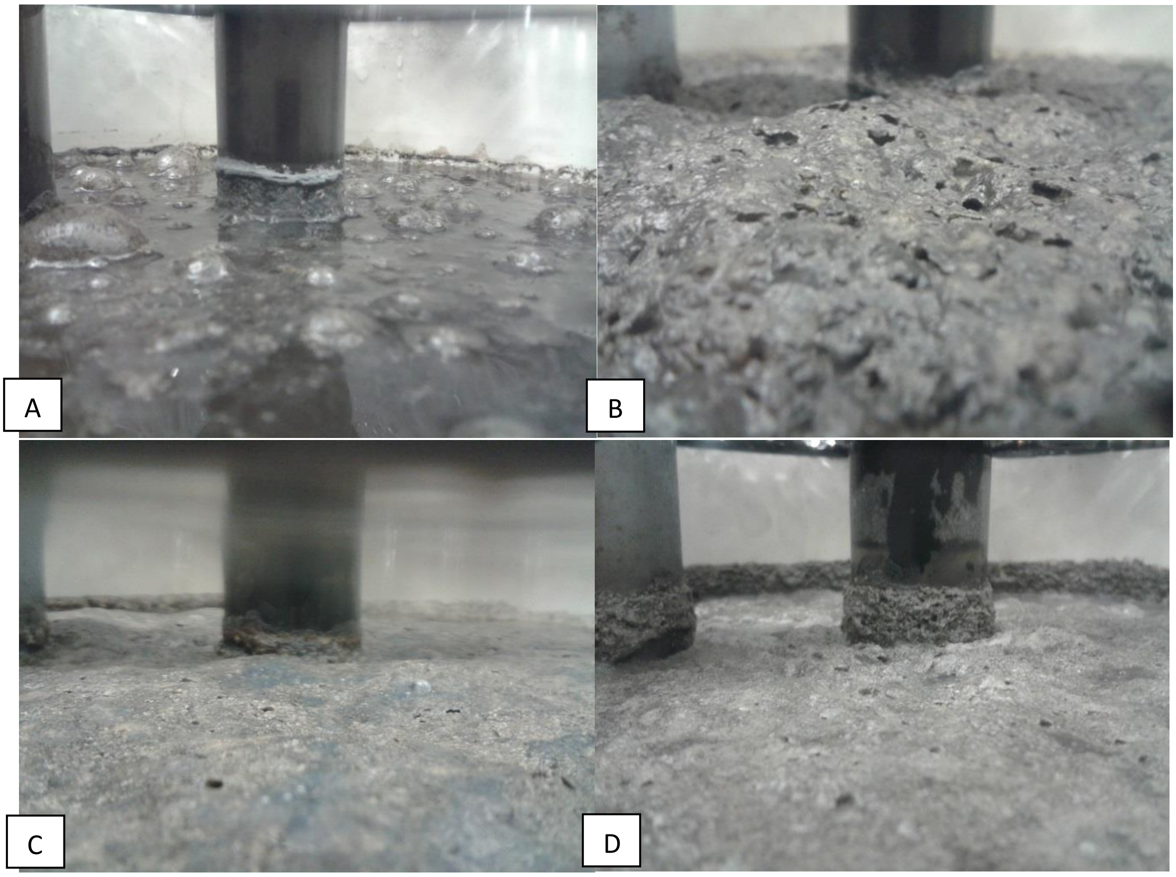

Figure 22: Crust/foaming layer in the reactors with minimal stirring on day 4 (A), day 16 (B), day 43 (C), and day 57 (D)

Crust/ foam formation was significantly influenced by the sludge used to inoculate the reactors at the start of the experiment. It was observed that the sludge settled to the bottom of the reactors and floated as a relatively solid crust on the surface of the liquid reactor content (Figure 22B). Due to the washout of sludge and solids during the experiment, the layer became more foamy and thinner (Figures 22C and 22D), but still more pronounced compared to reactors with continuous stirring, where no crust/foam layer was observed during the entire experiment (Figure 23: Surface *of the reactor content in a stirred reactor*

Figure 23: Surface of the reactor content in a stirred reactor

6.4.3. Process stability

Differences with respect to process stability were observed in the experimental variations (Figure 24). In the reactors with a temperature of 26°C, VFAs accumulated which resulted in a drop of the pH to about 6.5. Biogas production takes place in a pH range of 6.5 to 8.5, and values between 7 and 8 are recommended for an optimal process, while lower or higher values can be inhibitory. The results of this experiment show lower VFA concentrations and higher pH values in the mesophilic reactors (40°C), indicating a better process stability compared to the 26°C reactors. This is also shown by the higher values for alkalinity, which are presented in Figure 25.

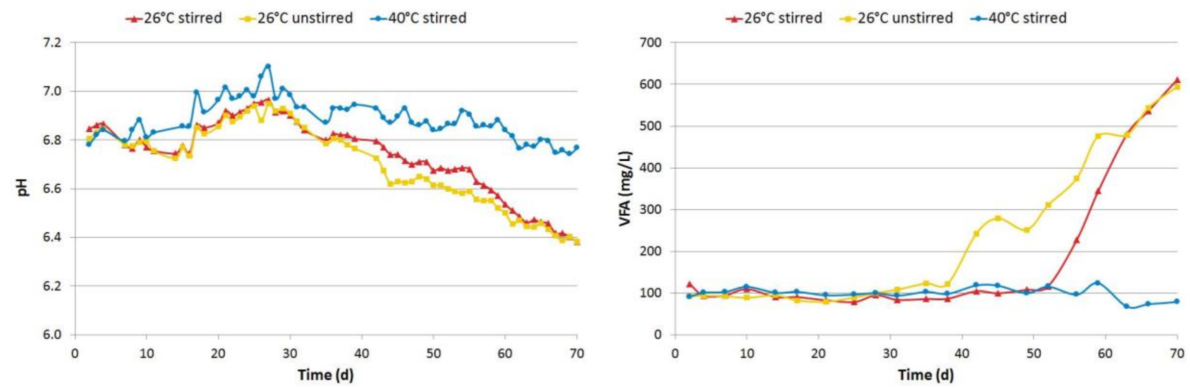

Figure 24: pH and concentrations of VFA

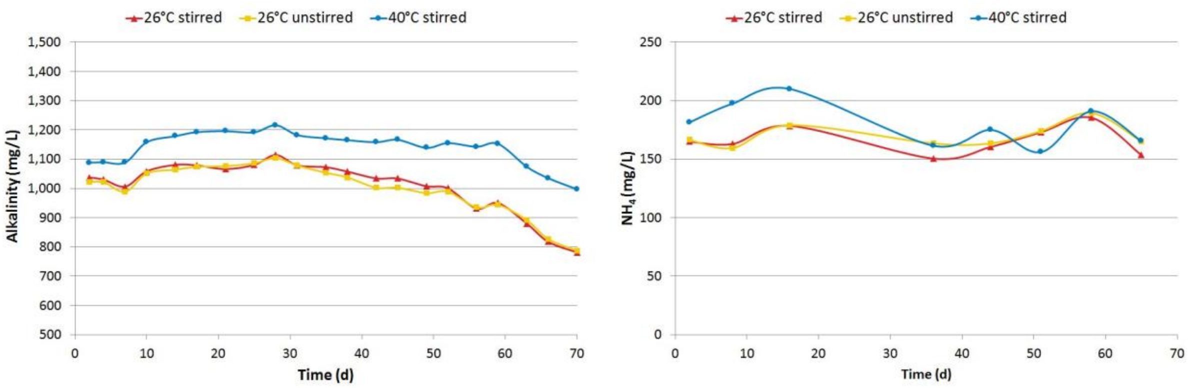

Figure 25: Alkalinity and concentrations of NH_4

The main buffering system relevant for the process of anaerobic biogas production at low pH (<7) is the hydrogen-carbonate/carbonate buffer (HCO_3^-/$CO3_2^-$), which is also influenced by the concentrations of NH_4 due to the formation of ammonium hydrogen carbonate (NH_4HCO_3). As shown in Figure 25, the alkalinity (expressed as equivalent of calcium carbonate), remained higher in the mesophilic digesters at 40°C, even at similar NH_4 concentrations, indicating again a more stable anaerobic process compared to the reactors with 26°C.

6.4.4. Biogas quantity and quality

Significant differences between the experimental variations were observed with respect to biogas production. As shown in Figure 26, the 40°C stirred reactors resulted in highest biogas production, as a result of better degradation and improved process stability.

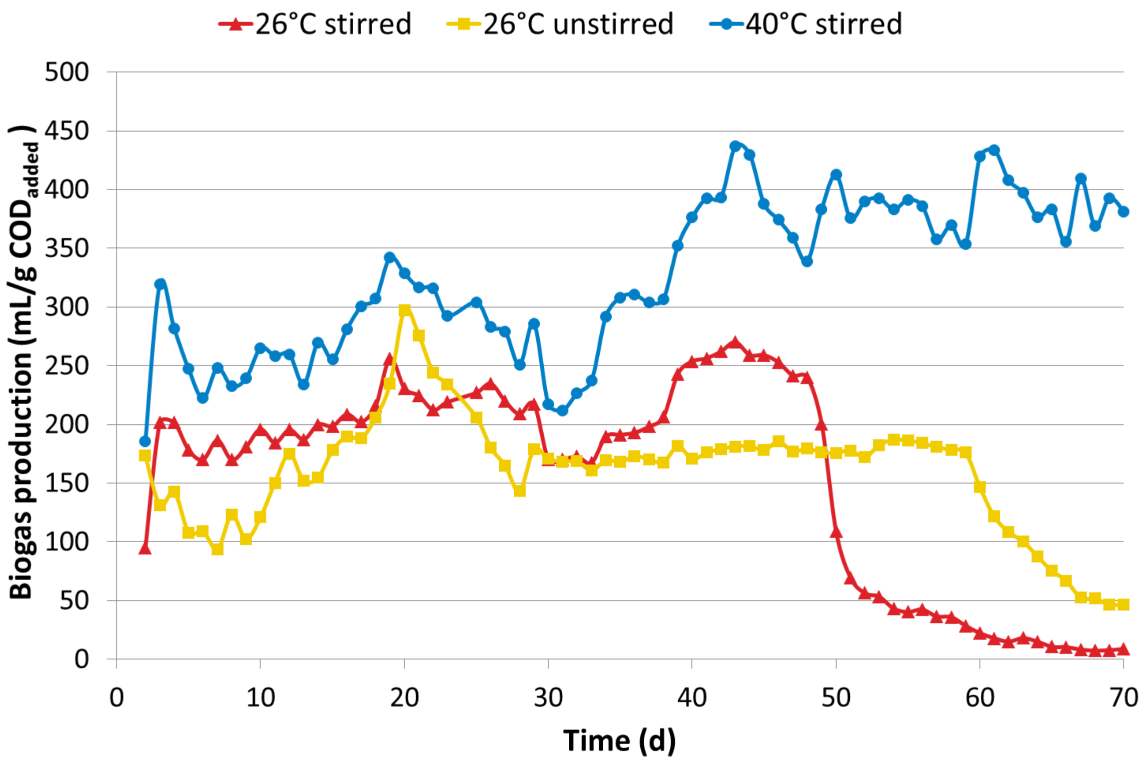

Figure 26: Biogas production in ml/g COD_{added} in the reactors

The 26°C stirred reactors produced more biogas for the majority of the time compared to the unstirred reactors, however, biogas production dropped sooner as a result of process failure (see section 6.4.3). Surprisingly, biogas production began to decrease without showing a significant accumulation of VFA or pH drop, which has been observed in the 26°C unstirred reactors previous to the decrease in biogas production.

Figure 27 shows the concentrations of methane and hydrogen sulphide (H_2S) in the biogas.

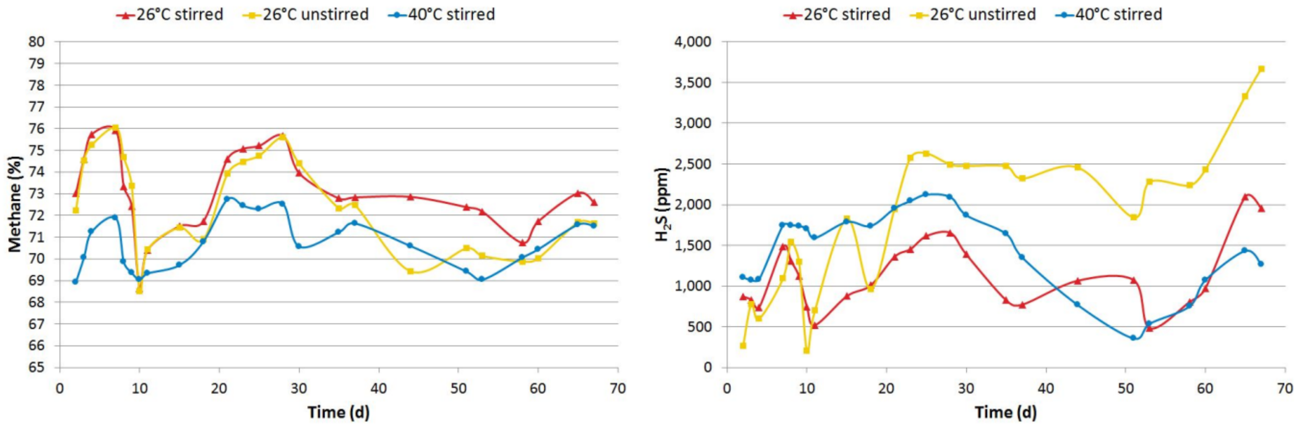

Figure 27: Methane and H_2S content in the reactors

The methane content in the biogas ranged between 70% and 75% with slightly lower values in the 40°C stirred reactors compared to the others, which might have been caused by the lower solubility of CO_2 at higher temperatures and the resulting higher share of CO_2 in the biogas. The concentrations of H_2S were highest (up to 3.672ppm) in the 26°C unstirred reactors, which could be related to the development of sulfate-reducing bacteria on the swimming layer on top of the surface.

7.0 DISCUSSION

The key discussion points derived from this work based on the project objectives are summarised below.

Crust formation in anaerobic lagoons can be attributed to four key issues:

1. Inadequate primary pre-treatment which fail to reduce wastewater fat levels;
2. Poor waste stream management practices leading to spills and shock loadings to the CAL;
3. Lack of process monitoring of the CAL resulting in physical and chemical parameters outside the optimum range thereby affecting the anaerobic digestion process;
4. Installation of poorly designed CAL technology which is unable to degrade high strength abattoir wastewater at desired organic loading rates and hydraulic retention times. Over recirculation of sludge can lead to the accumulation of sludge as a floating layer underneath the cover as evidenced by crust characterisation study.

The results of the first lab scale investigation showed that anaerobic digestion performance was not impacted negatively when lab scale reactors were operated at optimal conditions of temperature, stirring and addition of magnesium hydroxide to maintain optimal alkalinity levels. The experiment showed that even high FOG concentrations of up to 10,688 mg/L did not cause crust formation in the reactors. An inhibition of the anaerobic process by long-chain fatty acids was not observed. The process was stable with respect to VFA accumulation and pH value to an OLR of 1.4 g COD L-1d-1 when feedstock was added once a day. The average alkalinity of 1,282 mg/L CaCO3 Eq. was relatively low compared to the recommended values (2,000-3,000 mg/L), and a higher alkalinity would be advantageous to buffer changes in pH and to prevent it to fall below the minimum threshold (≈6.5).

The first lab scale experiment highlights that the production of biogas depends significantly on the feedstock concentration and composition. During the experiment between 1.5 and 26 liters of biogas were produced per liter of wastewater/feedstock and between 254 to 670 ml/g COD added. A key observation is the peak around day 178, which resulted from the addition of feedstock with a very high proportion (52%) of FOG regarding the total COD.

Higher alkalinity was reached in the period when 100% green stream was used as feed stock in the first experiment due to the higher nitrogen level in this wastewater stream. This shows the importance of knowing the composition of the different waste sources to optimize the anaerobic process.

The characteristics of the high-fat wastewater used in the second experiment ranged from 354 to 570 mg/L for volatile fatty acid (VFA) concentration and 530 to 5,385 mg/L for FOG. The formation of a crust/foam layer was only observed in the reactors with which were unstirred at ambient temperature (26°C). Differences were also apparent with respect to process stability. Reactors set at 26°C accumulated VFAs which resulted in a drop of the pH to about 6.5. The results of this experiment show lower VFA concentrations and higher pH values in the mesophilic reactors (40°C), indicating a better process stability compared to the 26°C reactors. This is also shown by the higher values for alkalinity. Significant differences between the experimental variations were observed with respect to biogas production. The 40°C stirred reactors resulted in highest biogas production, as a result of better degradation and improved process stability.

This second lab scale study suggests that it is difficult to specifically determine the maximum loadings of FOG that can be managed within anaerobic digesters. The investigation has highlighted that several factors can influence anaerobic digestion performance including temperature [ambient mesophilic (26°C) versus optimum mesophilic (40°C)] and the specific composition of the wastewater, including the relative level of FOG which contributes to COD loading and the level of nitrogen which contributes to alkalinity levels.

8.0 RECOMMENDATIONS

Key criteria for the management of FOGs in waste streams to assist industry in determining ideal plant operation to achieve optimal crust management and biogas production includes:

1. **Effective primary treatment** of the wastewater is essential to break down FOG into a dispersed and useable form or to ensure removal of excess FOG and solids. Primary treatment includes the use of:

- Screens (include static, vibrating, rotary, and screw presses) as the first stage of primary pre-treatment to remove solid material including fat particles, paunch and manure from the wastewater;
- Well –designed savealls which remove fat effectively;
- Adequately operated dissolved air flotation (DAF) systems.

2. **Good waste stream management practices** to avoid excessive loading rates which can lead to continuous crust formation. Shock loads can cause an accumulation of degradation products and by-products. Consequently, a digester can become overloaded, and the probability of excessive crust formation is high.

3. **Routine process monitoring of the CAL** to ensure key physical and chemical parameters are operating within the optimum range thereby ensuring efficient degradation and maximal biogas production.

4. **Installation of correctly designed CAL technology** which is able to degrade high strength abattoir wastewater at desired organic loading rates and hydraulic retention times. The CAL technology should take into account the degree of recirculation for mixing and ability to maintain optimum mesophilic temperatures.

The results of the lab scale trials using wastewater from an existing full-scale CAL in combination with field observations of CAL performance indicates that fat must be removed from the effluent to a level of < 300 - 400 mg/L and temperature maintained above 28-30°C. Alternatively, CAL technology which incorporates heating and stirring systems with the addition of chemicals to maintain optimum levels of alkalinity are required to degrade high-fat waste streams with FOG levels greater than 500mg/L. The lab scale investigations should be complemented by continued investigations of the performance of existing and new covered anaerobic lagoons.

9.0 BIBLIOGRAPHY

Appels, L, Baeyens, J, Degreve, J & Dewil, R 2008, 'Principles and potential of the anaerobic digestion of waste-activated sludge', *Progress in Energy and Combustion Science*, vol. 34, pp. 755-81.

Benefield, LA 2001, *Wastewater quality / strength / content*.

Bougrier, C, Albasi, C, Delgenes, J & Carrere, H 2006, 'Effect of ultrasonic, thermal and ozone pre-treatments on waste activated sludge solubilisation and anaerobic biodegradability', *Chemical Engineering and Processing: Process Intensification*, vol. 45, no. 8, pp. 711-8.

Cirne, D, Paloumet, X, Bjornsson, L, Alves, M & Mattiasson, B 2007, 'Anaerobic digestion of lipid-rich waste - Effects of lipid concentration', *Renewable Energy*, vol. 32, pp. 965-75.

CSIRO 2010, *Covered anaerobic ponds*, Meat Technology Update, 4th October 2010, www.meatupdate.csiro.au, www.meatupdate.csiro.au>.

Dasa, KT, Westman, SY, Millati, R, Cahyanto, MN, Taherzadeh, M & Niklasson, C 2016, 'Inhibitory effect of long-chain fatty acids on biogas production and the protective effect of membrane bioreactor', *Biomed Research International*, vol. 2016.

Desbois, AP & Smith, VJ 2010, 'Antibacterial free fatty acids: activities, mechanisms of action and biotechnological potential', *Applied Microbiology and Biotechnology*, vol. 85, no. 6, pp. 1629-42.

EPA 2002, *Development document for the proposed effluent limitations guidelines and standards for the meat and poultry products industry point source category (40 CFR 432)*, Office of Water, U.S. Environmental protection agency, Washington, DC.

Esposito, G, Frunzo, L, Giordano, A, Liotta, F, Panico, A & Pirozzi, F 2012, 'Anaerobic co-digestion of organic wastes', *Reviews in Environmental Science and Technology*.

Ferreira, L, Duarte, E & Figueiredo, D 2012, 'Utilization of wasted sardine oil as co-substrate with pig slurry for biogas production – A pilot experience of decentralized industrial organic waste management in a Portuguese pig farm', *Bioresource Techonology*, vol. 116, pp. 285-9.

Gerardi, M 2003, *The microbiology of anaerobic digesters*, John Wiley & Sons, Hoboken, New Jersey.

Golder Associates Pty Ltd 2009, *Anaerobic cover material vulnerability: Assessment of available cover materials*, A.ENV.0072, Meat and Livestock Australia.

Harris, P, Schmidt, T & McCabe, B 2017, 'Evaluation of chemical, thermobaric and thermochemical pre-treatment on anaerobic digestion of high-fat cattle slaughthouse waste', *Bioresource Technology*, vol. 244, pp. 605-10.

Harris, P & McCabe, B 2015, 'Review of pre-treatments used in anaerobic digestion and their potential application in high-fat cattle slaughterhouse wastewater', *Applied Energy*, vol. 155, pp. 560-75.

Jensen, P & Batstone, D 2012, *Energy and nutrient analysis on individual waste streams*, University of Queensland, Sydney,<.

Jensen, P, Sullivan, T, Carney, C & Batstone, D 2014, 'Analysis of the potential to recover energy and nutrient resources from cattle slaughterhouses in Australia by employing anaerobic digestion', *Applied Energy*, vol. 136, pp. 23-31.

Johns, M 1993, *Developments in waste treatment in the meat processing industry - a review of literature - 1979-1993*, Meat Research Corporation, Australia.

Koster, I & Cramer, A 1987, 'Inhibition of methanogenesis from acetate in granular sludge by long-chain fatty acids', *Applied and Environmental Microbiology*, vol. 53, no. 2, pp. 403-9.

Kougias, PG, Boe, K, Einarsdottir, ES & Angelidaki, I 2015, 'Counteracting foaming caused by lipids or proteins in biogas reactors using rapeseed oil or oleic acid as antifoaming agents', *Water Research*, vol. 79, pp. 119-27.

Kuglarz, M, Mrowiec, B & Bohdziewicz, J 2008, *Influence of kitchen biowaste addition on the effectiveness of animal manure digestion in continuous condition*, <http://www.wis.pk.edu.pl/media/file/konferencje/Kuglarz_Mrowiec.pdf>.

Laginestra, M 2012, *Covered anaerobic lagoons*, GHD Pty Ltd, Sydney,<.

Lienen, T, Kleyböcker, A, Brehmer, M, Kraume, M, Moeller, L, Görsch, K & Würdemann, H 2013, 'Floating layer formation, foaming, and microbial community structure change in full-scale biogas plant due to disruption of mixing and substrate overloading', *Energy, Sustainability and Society*, vol. 3, no. 1, p. 20.

Lindorfer, H & Demmig, C 2016, 'Foam Formation in Biogas Plants – A Survey on Causes and Control Strategies', *Chemical Engineering & Technology*, vol. 39, no. 4, pp. 620-6.

Long, J, Aziz, T, de los Reyes III, F & Ducoste, J 2012, 'Anaerobic co-digestion of fat, oil, and grease (FOG): A review of gas production and process limitations', *Process safety and Environmental Protection*, vol. 90, no. 3, pp. 231-45.

Ltd, GAP 2009, *Anaerobic cover material vulnerability*, Meat & Livestock Australia Limited, NORTH SYDNEY,<.

Ma, J, Zhao, Q-B, Laurens, LLM, Jarvis, EE, Nagle, N, Chen, S & Frear, CS 2015, 'Mechanism, kinetics and microbiology of inhibition caused by long-chain fatty acids in anaerobic digestion of algal biomass', *Biotechnology for Biofuels*, vol. 8, no. 141.

Martin-Gonzalez, L, Colturato, L, Font, X & Vicent, T 2010, 'Anaerobic co-digestion of the organic fraction of municipal solid waste with FOG waste from a sewage treatment plant: Recovering a wasted methane potential and enhancing the biogas yield', *Waste Management*, vol. 30, no. 10, pp. 1854-9.

Mayoh, R 2011, *Learnings from the Burrangong Meat Processor covered anaerobic lagoon*, Rycam Industrial Pty Ltd, Meat and Livestock Australia, Sydney,<.

McCabe, B, Harris, P, Baillie, C, Pittaway, P & Yusaf, T 2013, 'Assessing a new approach to covered anaerobic pond design in the treatment of abattoir wastewater', *Australian Journal of Multidisciplinary Engineering*, vol. 10, no. 1, pp. 81-93.

Mendes, A, Pereira, E & de Castro, H 2006, 'Effect of the enzymatic hydrolysis pretreatment of lipids-rich wastewater on the anaerobic biodigestion', *Biochemical Engineering Journal*, vol. 32, pp. 185-90.

MLA 2002, *Eco-efficiency manual for meat processing*, Meat and Livestock Australia, New South Wales,<.

Moeller, L, Goersch, K, Neuhaus, J, Zehnsdorf, A & Mueller, RA 2012, 'Comparative review of foam formation in biogas plants and ruminant bloat', *Energy, Sustainability and Society*, vol. 2, no. 1, p. 12.

National Research Council 1976, *Fat content and composition of animal products*, National Academy of Sciences, Printing and Publishing Office.

Nieman, C 1954, 'Influence of trace amounts of fatty acids on the growth of microorganisms', *Bacteriology Reviews*, vol. 18, no. 2, pp. 147-63.

Pereira, M, Pires, O, Mota, M & Alves, M 2005, 'Anaerobic biodegradation of oleic and palmitic acids: evidence of mass transfer limitations caused by long chain fatty acid accumulation onto the anaerobic sludge', *Biotechnology and Bioengineering*, vol. 92, no. 1, pp. 15-23.

Pronto, J & Gooch, C 2008, *Anaerobic Digestion at New Hope View Farm: Case StudyAnaerobic Study*, Cornell University.

Saharan, B, Sahu, R & Sharma, D 2011, 'A review on biosurfactants: fermentation, current developments and perspectives', *Genetic Engineering and Biotechnology*, vol. 2011, no. GEBJ-29.

UNSW 1998, *Treatment of abattoir wastewater using a covered anareobic lagoon*, UNSW CRC for waste management and pollution control.

White, T, Johns, M & Butler, B 2013, *Methane recovery and use at a meat processing facility: King Island*, Australian Government.

Wu, J-T, Chiang, Y-R, Huang, W-Y & Jane, W-N 2006, 'Cytotoxic effects of free fatty acids on phytoplankton algae and cyanobacteria', *Aquatic Toxicology*, vol. 80, no. 4, pp. 338-45.

Zheng, CJ, Yoo, J-S, Lee, T-G, Cho, H-Y & Kim, Y-H 2005, 'Fatty acid synthesis is a target for antibacterial activity of unsaturated fatty acids', *FEBS Letters*, vol. 579, pp. 5157-62.

10.0 APPENDICES

10.1 Appendix 1 Composition of waste streams at Site A

Source	Code	Sampling method *	Volume kL/day	TS (% FM)	VS (% TS)	pH	Total COD (mg L-1)	VFA (mg/L)	FOG (mg/L)	NH4 (mg/L)	Total N (mg/L	Total P (mg/L
Saveall South Combined sample	S6 F5	flow prop n=5	331	2.1	92.5	5.8	52656	1080	6100	84	366	66
Saveall South effluent post-screen	S8 F5	flow prop n=4	331	1.4	89.6	6.2	37063	1003	5525	116	316	56
Saveall South effluent post-DAF	S9 F5	flow prop n=4	331	0.8	85.0	6.7	21600	831	3000	130	339	48
Boning room	S4 F3	flow prop n=3	491	0.1	45.2	7.2	542	38	96	0	8	4
Decontamination	S12 F7	flow prop n=1	155	0.2	62.1	7.8	2005	121	1910	3	31	12
Saveall North Combined sample	S14 F9	flow prop n=4	552	0.4	60.2	8.1	4340	314	297	162	216	61
Combined Saveall North and South	S15 F10	flow prop n=2	1325	0.5	74.8	6.9	11925	553	1060	79	235	43
Combined cattle wash	S10	time prop n=2		0.2	48.6	8.7	2530	196	129	300	310	30
Paunch/green wash combined	S11	time prop n=2		0.6	69.8	7.1	10160	411	1013	28	125	152
Tripe wash pre-screen	S1	time prop n=2		2.4	94.1	5.6	40385	642	6700	27	95	113
Kill floor post-DAF	S17 F12	grab n=2	986	0.3	70.3	7.1	5715	321	470	35	150	44
Kill floor	S16 F12	grab n=3	986	0.7	84.8	6.7	18190	603	1300	34	333	62
Stick water	S3	grab n=4		1.8	78.0	4.7	30060	723	1080	62	1330	140

*n = number of sampling periods